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Methods and Energy Sources for Heating Subsurface Geological Formations, Task 1: Heat Delivery Systems

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METHODS AND ENERGY SOURCES FOR HEATING SUBSURFACE GEOLOGICAL FORMATIONS, TASK 1: HEAT DELIVERY SYSTEMS

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ABSTRACT

A one-year Cooperative Research and Development Agreement (CRADA) between Sandia Corporation and Shell Exploration and Production Company, titled "Methods And Energy Sources For Heating Subsurface Geological Formations," was executed on December 19, 2001. Its public abstract states that the parties "*will jointly evaluate a number of methods for delivering heat to oil-producing geologic formations. In the current effort, the parties will evaluate various heat delivery systems for pyrolysis of oil shale and evaluate the potential benefits of solar thermal energy to heat the subsurface at an oil shale site in Colorado.*" The deliverables to Shell from Sandia National Laboratories are separate companion reports on the evaluation of heat delivery systems, and on the potential benefits of solar energy. The present report describes the results of Sandia's evaluation of heat delivery systems.

Conceptual designs are presented for downhole molten salt, steam, combustion, and chemical heat pipe systems. Simple thermal/hydraulic models are developed, and their approximations are validated against more elaborate computational fluid dynamic and finite-element models. The simple models are able to simulate years of shale heating in minutes of PC time. Parametric studies that evaluate thermal and hydraulic performance are presented, and operating strategies are considered. For molten salt, steam, and combustion, the required materials are determined, structural issues are evaluated, and costs are estimated. The best near-term prospect appears to be molten salt, but it will require development of insulated tubing and freeze-prevention strategies. It is a good match for solar towers, fossil-fuel heating, and hybrid sources. Steam shares some of these same attributes, but is less attractive, because of high-pressure requirements for flow in smaller well casings, and two-phase flow issues. Downhole combustion could be very attractive in the mid-term, in terms of efficiency and simplicity of operation, but significant development is required, including combustors, igniters, and controls. Atmospheric emissions are an issue, and adaptation to a solar source is unlikely. Chemical heat pipes are an interesting long-term prospect, if cheap, reliable catalysts can be developed, and potential cycle performance is verified. They offer good match to solar power towers, and efficient long-distance power transmission. Next steps for a near term, molten-salt demonstration are recommended.

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1. INTRODUCTION

A description of the enormous worldwide resource of oil shale, and its past exploitation, can be found in "Oil Shale Technical Data Handbook" [1]. Oil shale is typically an impermeable matrix of inorganic and organic solids. The organic content can be obtained by fracturing the matrix, followed by heating to decompose the organic solids to liquids and gases. A recent patent by Shell Oil Company (Houston, TX) details a method to accomplish this *in situ*, by injecting heat into the shale via one or more injection wells, thereby fracturing the shale and producing organic fluids to one or more producer wells [2]. Figure 1 illustrates this method.

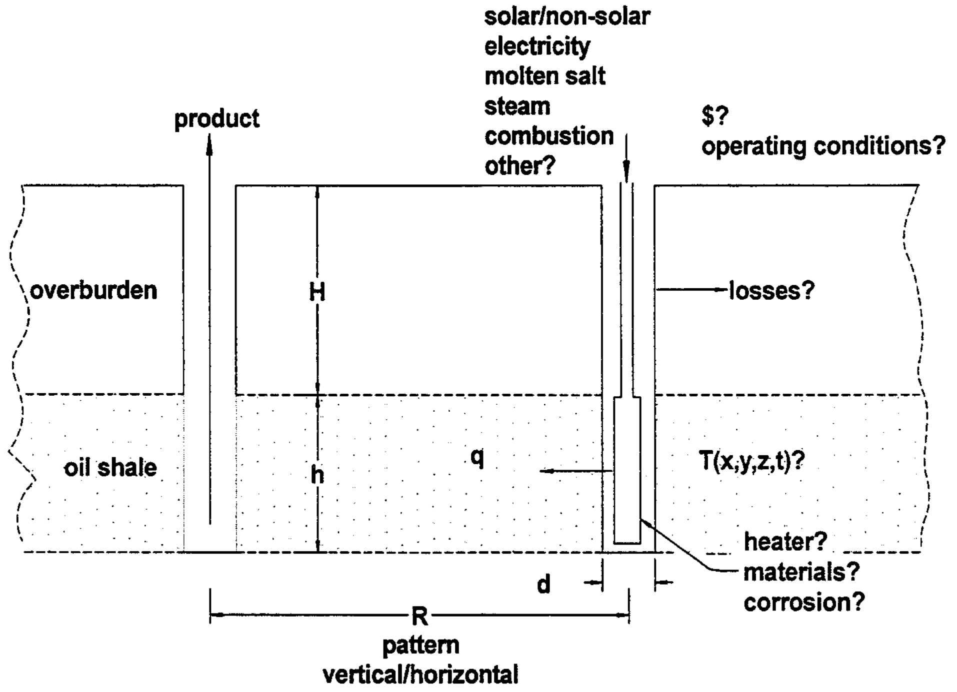


Figure 1. *In situ* heating method.

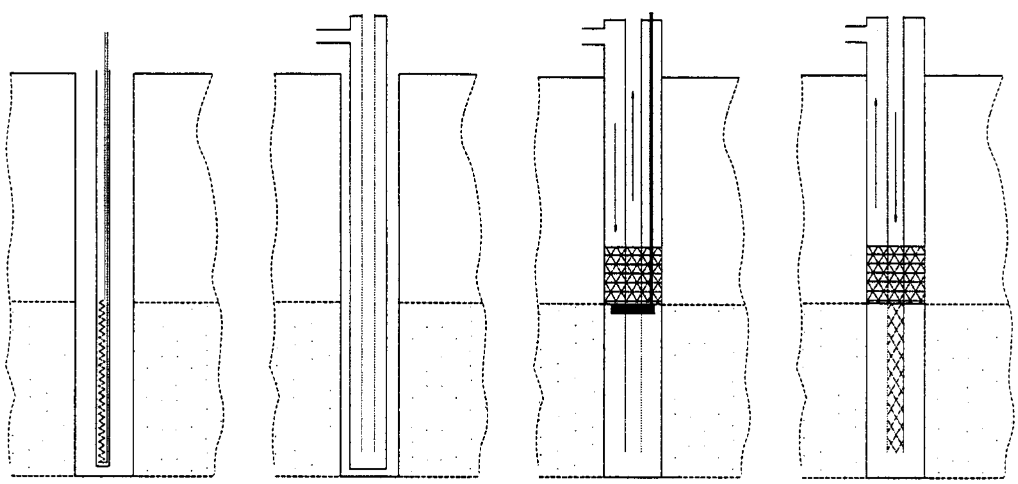
To explore various heat delivery methods for the Shell approach, and to evaluate the potential benefits of solar power as a heat source, a one-year Cooperative Research and Development Agreement (CRADA) between Sandia Corporation and Shell Exploration and Production Company (Shell E&P), was executed on December 19, 2001. The CRADA public abstract states that the parties "will jointly evaluate a number of methods for delivering heat to oil-producing geologic formations. In the current effort, the parties will evaluate various heat delivery systems for pyrolysis of oil shale and evaluate the potential benefits of solar thermal energy to heat the subsurface at an oil shale site in Colorado." The basis for Sandia's participation includes its current activities in concentrating solar power, geothermal technology, and combustion, its previous experience in oil-shale development and enhanced oil recovery, and its long history in systems integration. The complete Statement of Work for Sandia is presented in APPENDIX A: STATEMENT OF WORK. It describes two technical report deliverables: (1) a comparison and evaluation of heat delivery systems; and (2) an evaluation of potential benefits of using solar thermal energy (to heat shale).

Sandia presented a preliminary assessment of heat-delivery options and solar benefits to Shell E&P on March 12, 2002. Vu-graphs from this meeting are presented in APPENDIX B: 3/12/02 VU GRAPHS. A second meeting was held on September 11, 2002, to present the status of the work at Sandia, and cost estimates for various possible activities for succeeding years. Vu-graphs from this meeting are presented in APPENDIX C: 9/11/02 VU GRAPHS. After the March meeting, and following feedback from Shell E&P, Sandia developed a project plan, which it evolved with Shell E&P into final form. This plan is presented in APPENDIX D: CRADA PROJECT PLAN. It includes a statement of objectives, scope, restrictions, assumptions and constraints, a detailed list of activities and estimated times, and a Gantt chart. Here, we report on those activities that concern the evaluation of heat delivery systems: specifically, system selections; designs; analyses; operational issues; and recommendations. Results on the evaluation of solar potential are presented in a companion report [3].

2. HEAT DELIVERY OPTIONS

A brainstorming session was held at Sandia to identify as many means as possible for delivering heat to subsurface geological formations. The various concepts were then assessed in order to decide which would be further analyzed in the present project. Concepts were evaluated based on their near-term practicality, with regard to cost, efficiency, scale-up potential, and public acceptance. The results of the brainstorming session, and of the post-brainstorm assessment of each concept, are presented in APPENDIX E: RESULTS OF BRAINSTORMING.

The conclusion was, that only a few concepts merit further evaluation at this time. They are: (1) sensible heat delivery (Figure 2b), using molten nitrate salts, or possibly steam, heated in surface plants; (2) downhole combustion (Figure 2c), preferably burning fuel produced on site; and (3) chemical heat pipes (Figure 2d), in which syngas is endothermically produced in surface plants, and exothermically converted back to feedstock down hole.



(a) Electric **(b) Sensible heat** **(c) Combustion** **(d) Chemical HP**

Figure 2. Shale heating concepts

Chemical heat pipes are not a near-term option, and thus will be discussed in much less detail than the others. But they are included, because they offer efficient downhole delivery (comparable to downhole combustion), and they make possible the distant off-site location of the surface plant. Each concept could have either a solar or fossil-fueled surface plant. Electric heating (Figure 2a) was also identified as an interesting option, but because it is receiving considerable attention at Shell E&P, not one that warranted detailed evaluation here. However, it is considered tangentially, in our modeling of heater performance, and especially in comparing the sensitivity of heating methods to variations in shale thermal conductivity.

In Section 3, we present high-level designs and evaluations for each selected downhole delivery concept. In Section 4, we compare the various concepts, discussing their strengths and weaknesses. Section 5 presents our recommendations for future steps.

3. DOWNHOLE HEATER DESIGNS

3.1 OVERVIEW

Shell E&P defined a nominal set of conditions for our concept evaluations:

1. Total project -- 1.25 mile x 1.25 mile, 24 years duration
2. Maximum heated part of project at any time -- 0.5 mile x 0.5 mile
3. Overburden zone -- 800 ft. (with a range of 400-1000 ft.)
4. Shale interval -- 800 ft. (with a range of 300-850 ft.)
5. Fisher assay -- 26 gallons oil/ton of shale
6. Triangular injector pattern -- 30-ft. spacing (with a range of 20-40 ft.)
7. Shale heat injection rate -- 250 Watt/ft.
8. Well casing – 6 in. (with a range of 6-12 in.)

In addition, Shell E&P indicated that the heating objective is to bring most of the shale to 600 F (315 C) as quickly as possible, while limiting dolomite decomposition (temperatures above ~600 C) to a small volume around the injection well. Ideally, the heater should operate at about 1000 F (538 C). Also, Shell E&P pointed out that the shale thermal conductivity k could vary, in as little as several vertical feet, from 1.51 W/m-K (10 gallons/ton shale) to 0.97 W/m-K (40 gallons/ton shale). Aside from comparing heater robustness with regard to this variation, properties variations are to be approximated as constant. For direct comparison with results presented in Ref. 2, we assumed a thermal conductivity of 1.35 W/m-K, and a thermal diffusivity of 0.0066 cm^2/s.

3.2 DOWNHOLE MOLTEN SALT

3.2.1 Concept

Downhole molten salt belongs to the class of heaters that transport power as sensible heat. Downhole molten salt heaters have the following features:

1. Surface heat source -- this could be a fossil-fueled heater, a solar heater, or a hybrid heater (solar plus fossil fuel). It includes the distribution piping to carry the molten salt to the wells, and to return the salt to the source.
2. Heat transfer fluid – this must be a fluid suitable for temperatures higher than the desired shale temperature. Steam (and air) will be considered in another section of this report. Oils are expensive, and they have restrictive decomposition-temperature limits -- for example, Therminol VP-1, a synthetic oil used in solar trough plants, costs about $0.82/lb, and has a maximum-use temperature of 400 C [4, 5]. Molten nitrate salts, discussed in more detail below, are cheap (as little as $0.22/lb), and can be used at temperatures as high as 565 C [5].
3. Downhole heater – the molten salt needs to be ducted from the wellhead to the shale interval and back, delivering as much of its power as possible to the shale. This means that heat transfer between the downcomer and riser should be minimized, as should heat transfer to the overburden (heating the overburden would only be advantageous if the injection well were also a producer well, in which case, it could be used to prevent product condensation). Because there are no pipe sealants that are compatible with nitrate salts, the piping must be all-welded.

Except for the heater, the downhole piping must be insulated to minimize both overburden loss and heat exchange between the downcomer and riser. These facts, and the all-welded requirement, suggest that the salt system should be a self-contained system within the well casing. The most compact and efficient system consists of concentric pipes, with the downcomer inside of the riser. In the shale interval, heat transfer from the riser to the casing is accomplished by radiation, and the riser outside diameter is not insulated. In the overburden zone, the salt in the riser will be at least as hot as the shale. This heat must be conserved, so the riser outside diameter is insulated throughout the overburden zone. This insulation needs to be mechanically protected, but does not need to be hermetically sealed. In contrast, the downcomer must be insulated over its entire length. Because the insulation is between salt streams, it must be isolated from the salt to prevent salt intrusion. Most commercial steam injection tubing has sealed insulation, but is not suitable here, for a number of reasons, including the fact that it has threaded joints, and it is limited to fluid temperatures below about 350 C. In the most robust systems, the insulation is contained between concentric pipes that are welded together. To limit thermal stresses in the pipes under service conditions, the pipes are pre-stressed, with the inner one in tension. As the structural analysis presented later shows, pre-stressing is not feasible for the present conditions. The alternative that is proposed here is illustrated in Figure 3. This is an all-welded arrangement that could be field-assembled, or factory made and spooled, with the insulation open to the atmosphere at one end. The well-head arrangement shown in Figure 3 accommodates differential thermal expansion, while preventing molten salt from intruding into the insulation. It does not require flex hose connections, which can be unreliable, or flexible joints, such as ball joints, which are not available for molten-salt service.

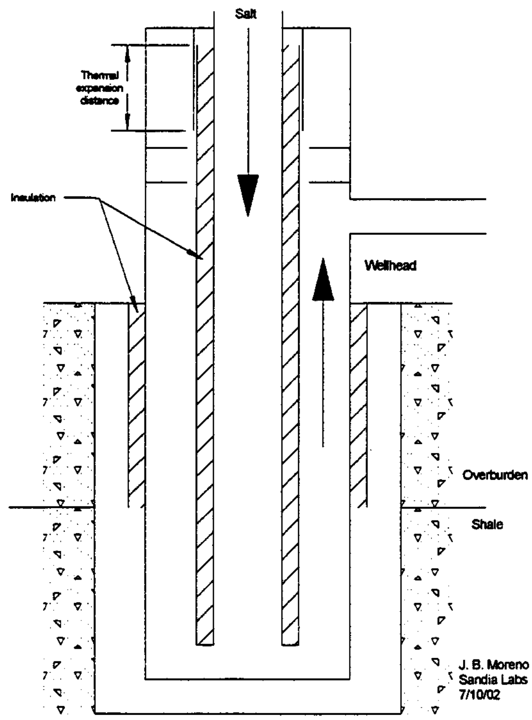


Figure 3. Molten-salt insulated string and well-head concept.

3.2.2 Functional design

3.2.2.1 Materials

The injection string is the major component in the molten salt shale heater. It is envisioned here as two separate items, shown in Figure 3: (1) the downcomer, consisting of two concentric tubes, with insulation filling the annular space, and (2) the riser, surrounding the downcomer, and insulated in the overburden zone. A great deal of development work has been done to qualify piping for solar salt in power tower plants: at the highest-temperature use of nitrate salt, austenitic stainless steel or high-chromium (>9%) Cr-Mo steel is needed for adequate corrosion protection [6]. Molten nitrate salts cannot be contained in pipe with threaded couplings -- the salts are strong oxidizers at high temperature, and are thus incompatible with all existing pipe sealants [7]. All-welded construction is necessary.

The insulation needs to be high-temperature capable. Compressive strength would also be an advantage, reducing the need for centralizers and other protection. For the downcomer, where space is at a premium, the insulation needs to have very a low thermal conductivity. In an experimental study of insulated pipe, Sandia found multi-foil vacuum-insulated pipe to be state-of-the art [8]. Oil Tech Services, Inc. (OTSI, Houston, TX) makes a pre-stressed vacuum-insulated pipe, using multi-foil insulation. OTSI quotes a thermal conductivity for this insulation of about 0.005 W/m-K at 354 C, and for the joint, a higher effective conductivity, 0.026 W/m-K (because of losses at the couplings). A non-vacuum alternative insulation is microporous silica blanket. ITP Interpipe (Louveciennes, France) claims that the microporous insulation it uses in undersea pipelines, Izoflex, has a thermal conductivity of 0.02 W/m-K at 565 C, and a maximum-use temperature of 900 C [9]. For a similar material, Excelflex Flexible (16#), ThermoDyne (Elkhart, IN) claims 0.046 W/m-K at 565 C [10].

Salt selection is based primarily on temperature limits (freezing at the low end, decomposition at the high end), and on cost. A 7:53:40 wt% mixture of $NaNO_3$:KNO_3:$NaNO_2$ called Hitec is commonly used in the chemical industry [11]. One drawback of Hitec is that, if any air is present in the system, the nitrite will convert to nitrate, raising the freezing point. It costs about $0.42/lb, freezes at 142 C, and has a maximum use temperature of 535 C [5]. Automatic water dilution is possible to avoid solidification on startup and shutdown [12]. A 60:40 wt% mixture of $NaNO_3$:KNO_3 called solar salt has been used in several solar central receiver ("power tower") projects [13]. It costs about $0.22/lb, freezes at 220 C, and has a maximum use temperature of 565 C [5]. Although its freezing temperature is relatively high, its other attributes make it the baseline choice here.

3.2.2.2 Structural analysis

Molten-salt heating has a number of structural issues, including:

1. Feasibility of pre-stressed vacuum-insulated pipe (VIP) for the downcomer.
2. Stresses in downcomer, version with insulation open to atmosphere at one end.
3. Frictional forces in downcomer, opposing thermal expansion.
4. Stresses in riser.
5. Creep at operating temperature.

VIP downcomer feasibility: consider pre-stressed concentric pipes with wall cross sectional areas A_i and A_o, forming joints of length L. For the moment, ignore hydrostatic pressure and the weight of the hanging string, focusing only on the loads imposed by pre-stressing and differential thermal expansion. Then, the initial axial pre-stresses σ_i and σ_o are related by the force balance

$$A_i \sigma_i = -A_o \sigma_o,$$

and during heating, any subsequent changes are related by

$$A_i \Delta\sigma_i = -A_o \Delta\sigma_o.$$

The changes in total axial strain induced by temperature must also be equal:

$$\alpha_i \Delta T_i + \Delta\sigma_i/E_i = \alpha_o \Delta T_o + \Delta\sigma_o/E_o.$$

Here, E is the elastic modulus and α is the coefficient of thermal expansion, properly averaged over the temperature excursion. Combining equations,

$$\Delta\sigma_i = E_i (\alpha_o \Delta T_o - \alpha_i \Delta T_i)/(1+A_i E_i/(A_o E_o))$$

If the inner pipe is axially pre-stressed to σ_p, then its axial stress in service is

$$\sigma_p - E_i (\alpha_i \Delta T_i - \alpha_o \Delta T_o)/(1+A_i E_i/(A_o E_o)).$$

The stress in the outer pipe is just - A_i/A_o times this. Now add to the analysis the weight of the hanging string(conservatively neglecting buoyancy), W, which is supported by the changes in stress in each pipe:

$$W = A_i \Delta\sigma_i' + A_o \Delta\sigma_o'$$

It causes an additional strain, equal in both pipes,

$$E_i'/\Delta\sigma_i' = E_o'/\Delta\sigma_o'$$

Where E' is the elastic modulus at the temperature of interest. Combining these two equations,

$$\Delta\sigma_i' = W/(A_i+A_o E_o'/ E_i')$$

And

$$\Delta\sigma_o' = W/(A_i E_i'/ E_o' + A_o)$$

Then the total stress in the inner pipe is

$$\sigma_p - E_i (\alpha_i \Delta T_i - \alpha_o \Delta T_o)/(1+A_i E_i/(A_o E_o))+ W/(A_i+A_o E_o'/ E_i'),$$

and in the outer pipe,

$$-(A_i/A_o)([\sigma_p - E_i (\alpha_i \Delta T_i - \alpha_o \Delta T_o)/(1+A_i E_i/(A_o E_o))]+ W/(A_i E_i'/ E_o' + A_o).$$

Consider the case when the properties and cross-sectional areas are the same for both pipes. Then the stresses are (plus sign for the inner pipe)

$$\rho gL \pm [\sigma_p - E\,\alpha\, ((\Delta T_i - \Delta T_o)/2),$$

where L is the length of the string. Assuming values representative of 316L stainless steel,

$$\rho = 0.29 \text{ lb/in}^3,$$

$$E = 29 \times 10^6 \text{ psi},$$

$$\alpha = 19.3 \times 10^{-6} \text{ in/in-C},$$

and a string length of 1600 feet, with ΔT in units of deg C, the stresses are:

$$5600 \text{ psi} \pm [\sigma_p - 280\ (\Delta T_i - \Delta T_o),$$

At ambient temperature, the stresses are

$$5600 \text{ psi} \pm \sigma_p.$$

We can approximate $\Delta T_i - \Delta T_o$ by the difference between the molten salt temperatures in the downcomer and riser (i.e. the molten-salt heat-transfer film coefficients are large). The largest value will occur at early times, but even then, the temperature in the riser must be above the freezing point, insured perhaps by pre-heating with air or electricity. Assuming the worst case, $\Delta T_i - \Delta T_o = 565$ C-220 C, gives stresses of

$$5600 \text{ psi} \pm [\sigma_p - 96600 \text{ psi}).$$

The stresses at ambient and early-time service conditions are plotted versus pre-stress, in Figure 4.

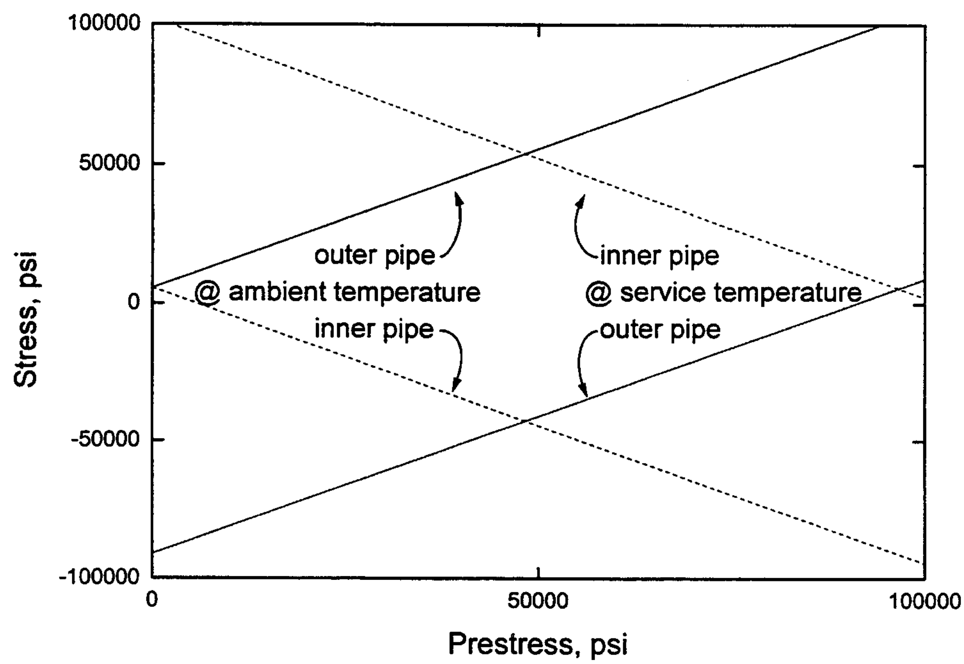


Figure 4. Stresses as a function of pre-stress, for vacuum-insulated pipe

The yield strength of 316L stainless steel is about 32 kpsi at ambient, and 15 kpsi at 565 C [14]. The stress for 10^{-5} % creep strain per hour is about 13 kpsi at 565 C [14]. It is clear from Figure 4 that no choice of σ_p can keep the stresses below these limits for both ambient and service conditions. It is also clear that the string weight is of secondary importance.

Summarizing: the use of vacuum insulated pre-stressed pipe (VIP) appears infeasible in the present application, at least for 316L stainless steel and similar alloys. It remains to be seen if VIP might be feasible with other alloys. For example, 9Cr-1Mo grades 91 and 911have yield strengths of 60 and 64 kpsi, respectively [15], which is considerably better than 316L stainless steel. An assessment of this possibility will require further analysis, along with acquisition of a full set of mechanical properties for any such candidates.

<u>Stresses in downcomer with open insulation:</u> the downcomer, supported as shown in Figure 3, will have stresses imposed by (a) its own weight (greatest at the wellhead), (b) the hydrostatic pressure of the molten salt (greatest near the bottom of the well), and (c) the shear forces associated with the flow of molten salt. The weight of the insulation can be neglected. The density of the salt is, at most, about 120 lbs/ft^3. The hydrostatic pressure at the bottom of a 1600-ft well is thus

$$120 \text{ lbs/ft}^3 \times 1600 \text{ ft}/144 \text{ in}^2/\text{ft}^2 = 1333 \text{ psi.}$$

Assume the downcomer is two nested 316L stainless steel pipes with the following diameters:

$$D_{ii} = 1.38",$$
$$D_{io} = 1.66",$$
$$D_{oi} = 1.995",$$
$$D_{oo} = 2.375".$$

Since the space between the pipes is nominally at atmospheric pressure, the hoop stress in the inner pipe, caused by the salt hydrostatic pressure, is 6570 psi. This is well below the yield or creep stresses of concern (see preceding section). The collapse pressure of the outer pipe is about 2.2 E $(t/D_{oo})^3$ = 32670 psi, where t is the wall thickness [16]. This is far above the actual pressure, so collapse is not a possibility.

The empty weight of a 316L stainless steel string is calculated to be 10970 lbs, and the axial stress in the inner pipe, which supports the entire string, is 16370 psi. This is well below the yield stress at ambient temperature. However, at 565 C, it is somewhat above the stresses for yield and 10^{-5} % creep strain per hour. The molten salt buoyant force is about 3900 lbs. When in place, the salt eliminates the yield and creep concerns by reducing the axial stress to 10550 psi.

The shear forces associated with the flow of molten salt are calculated in the performance model. They turn out to be unimportant here. For example, for a salt flow rate of 1.2 kg/s, the shear force is about 24 psi x (3.14/4) x D_{ii}^2 = 36 lbs.

Hot salt entering the inner pipe will cause it to expand. If the string is first preheated to 220 C, the temperature change will be 565 C –220 C = 345 C. This will lower the bottom of a 1600-ft string by approximately 11 feet. As the salt flows into the riser, it will expand the outer pipe a similar amount. Since this pipe is supported at the bottom, it must be supported against buckling with centralizers. Sideways deflections will still occur, but will be limited by the centralizers. As axial expansion of the outer pipe begins, contact forces between the pipe and the centralizers will generate frictional forces, which resist the axial displacements. The frictional forces may, in turn, cause larger contact forces. This is a potentially unstable situation, which could result in pipe lockup, and which will require further analysis, and testing.

Summarizing: while a more detailed analysis will be necessary to design an injection string with an open insulation package, the present analysis indicates that the stresses should be manageable.

Stresses in the riser: the riser is envisioned as a closed-end pipe, hung from the well head, with insulation applied to its outside diameter, as in Figure 5. A size consistent with the example of the preceding section has an inside diameter of 2.992" and an outer diameter of 3.5". For a 1600-ft well, the weight of the riser is 14420 lbs and the weight of the molten salt is 5470 lbs. The axial stress in the riser at the well head is 7680 psi, well below the level for yield or for 10^{-5} % creep strain per hour at 565 C.

3.2.2.3 Costs

The main costs for a downhole molten salt heater are the insulated downcomer, the partly-insulated riser, and the well head. The cost of vacuum-insulated string in the size considered here is about $37/ft [17]. A spooled factory-produced downcomer with open insulation package may be feasible for less. The same is true of an externally-insulated riser. The well head is a specialty item that will need to be costed. For present purposes, we estimate $50k. These items total, for a 1600-ft. well, $118,450. The cost of salt will depend on the amount of thermal storage required, and the type of salt used. For no storage, we estimate that twice the salt in the heater will be needed, or about 10,000 lbs. If Hitec is used, this will cost $4400. Enough Hitec to provide 300 kW for 16 hours at a ΔT of 50 C amounts to 5 x 10^6 lbs, costing an additional $220,000, however, field management strategies would probably increase the ΔT by times 5, reducing the cost to $45000. The cost of solar salt would be about ½ this, or $22500.

3.2.3 Performance analysis

3.2.3.1 Heater Models

The flow of salt in the injection string delivers heat to the subsurface geologic formations, which in turn conduct the heat away from the casing in a transient manner over very long periods of time. The time-dependent spatial distribution of temperature in the reservoir, as well as temperatures and pressures within the heater, need to be estimated in order to evaluate the method. We modeled this complex coupled problem two different ways. The first is a simple representation that has the advantage of fast execution, essential for our parametric studies. It is also easily modified and adapted, allowing treatment of many different scenarios (for example, wells in series). The second approach is detailed finite-element models, including all modes of heat transfer, arbitrary dimensionality, and variable properties. Its very large computing times do not allow it to be used routinely. But with it, we are able to assess the relative importance of each effect. We can also use it to validate the simple model. A description of the each of these models follows.

3.2.3.2 Simple molten-salt model

The simple model is correlation-based, consisting of two parts: (1) a quasi-steady thermo-hydraulic model for the fluid flow and heat transfer within the well casing; and (2) a transient-conduction model for the heat transfer in the shale and overburden zones. Both parts of the model are axisymmetric. This is appropriate for two situations: (1) a single injection well at early times, before neighboring features affect the symmetry; and (2) an injection well in a repeating pattern, far from the edge of the field. Figure 5 illustrates the cylindrical approximation of the geometry surrounding the well for the case of a triangular pattern.

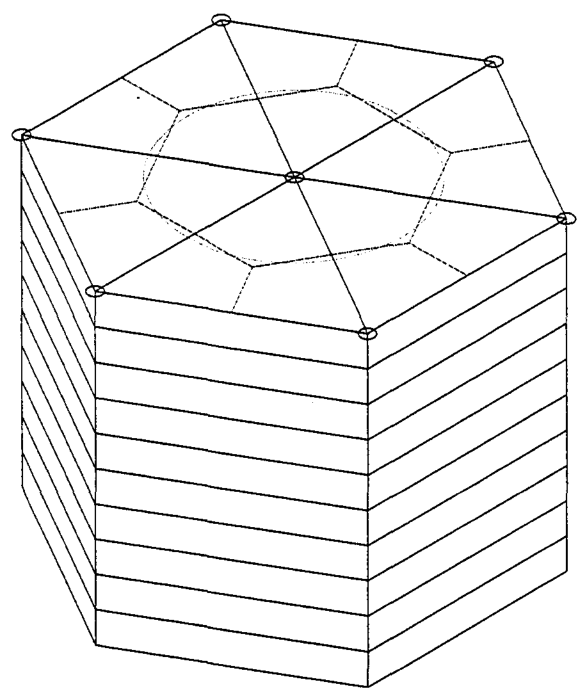


Figure 5. Approximation of the geometry surrounding an injection well in a triangular pattern as cylindrical (hexagonal adiabatic boundary approximated as circular).

The thermo-hydraulic part uses film coefficients to calculate radial heat transfer in the molten salt, given the salt flow rate, its inlet temperature, and the instantaneous casing axial temperature distribution. It includes conduction through the insulation packages (between the fluid streams and to the injection-string outer diameter), and radiant exchange between the outer diameter of the string and the inner diameter of the casing. The core of the method is a shooting technique to integrate the quasi-steady molten salt flow equations from the bottom to the top of the downcomer and riser. The flow equations are written in one-dimensional first-order finite-difference explicit form. The shooting technique begins with a guess for the bottom-hole salt temperature, repeatedly calculating the salt temperatures from bottom to top, with sequentially refined guesses, until the specified inlet temperature is matched. The method concludes with a correlation-based calculation of the pressure loss in the fluid flow.

The conduction part solves the shale and overburden transient cylindrical conduction equation for one time step, given the heat flux at the casing from the thermo-hydraulic part. It does this for a stack of non-communicating disks that approximate the well surroundings (Figure 5). The conduction equation is discretized both in time and on a non-uniform radial grid. The time discretization is fully implicit. The result is a tri-diagonal matrix equation for each disk in the formation. The casing temperature at the new time serves as the boundary condition for a new thermo-hydraulic solution. The quasi-steady thermo-hydraulic part works because the characteristic time for heat transfer within the casing is much shorter that the characteristic time of the formation.

The simple model was programmed in MathCad Professional 2000i. The code listing is presented in APPENDIX F: MATHCAD MODEL. The molten salt code requires about 4 minutes of Pentium-II (300 MHz) processor time to model four years of heating. The code consists of four sections, spanning 15 MathCad worksheet pages: (1) data input and setup, (2) equation solving, (3) energy-balance checks and results displays, and (4) pressure loss calculations. The heart of the code is a set of nested loops containing the equation solvers, which include both the thermo-hydraulic shooting calculation and the conduction tri-diagonal matrix-equation solver. The salt temperatures, the flux at the casing, and the reservoir temperatures, are all contained in the solver output matrix M.

3.2.3.3 Finite-element models and validation of the simple model

Finite element analysis (FEA) was used to validate the simple models. The FEA code used is called COSMOS/M, developed by Structural Research and Analysis Corporation (SRAC). COSMOS/M is a general-purpose code, used for structural analysis, heat transfer, and fluid flow. Features that relate to this project include both 2-D and 3-D models, transient analysis, time dependent boundary conditions, radiative heat transfer, and conjugate heat transfer.

The first model we made was a simple 2-D conduction model considering a 7-spot pattern. Test cases from Figure 7 and Example 2 of Shell's patent [2] indicated good agreement, especially considering that all of the assumptions in the Shell patent were not known. Details of the results can be found in the Sandia's vu-graphs for the March 12, 2002 meeting (APPENDIX B: 3/12/02 VU GRAPHS).

After the March 12, 2002 meeting, more complex models were developed. These models included the entire depth of both the overburden and the shale. The models developed fell into one of four categories:

- –3-D, with fluid flow
- –3-D, no fluid flow
- –2-D, no fluid flow
- –2-D, with fluid flow

All models used the radiation heat transfer from the molten-salt riser outer diameter to the formation. Constant material properties were also used.

From an FEA point of view, this was not a simple problem. The major difficulty is that the aspect ratio of the project is very large – many layers of materials (pipe, insulation, salt, air) contained within a 6" (typical) well casing, whereas a typical depth is 1600'. Considering that the aspect ratio of the elements can only be on order of 10, there would have been too many elements to run on a PC: To solve this problem, a coordinate transformation was performed in the axial (vertical) direction. If the depth of the well is transformed by a factor of N ($z' = z/N$), then the governing equations dictate that the following changes in properties be made in the axial direction:

$$k' = k/N^2$$
$$c_p' = c_p/N$$

This transformation makes the model size feasible to run on a PC.

3-D, with fluid flow

The most complex model attempted was the full 3-D description with fluid flow. However, this turned out be much too computational-intensive. A model was developed and meshed, and run for a couple of days of simulation. Extrapolating the run time to 4 years indicated run times of several months. At that point, the Sandia computational group was contacted. We found that their codes are not tailored to this type of problem. In addition, due to "run-time overhead" of their codes, they would only be about twice as fast as a PC FEA code. Moreover, personnel in this group confirmed the complications of this seemingly simple problem. It is not any one aspect, but the combination of complexities that produce the difficulties. These include radiation heat transfer, anisotropic properties, transient boundary conditions, and the extremely long simulation time of 4 years.

Because of the complications listed above, we decided that a 2-D model was appropriate for screening. The big advantage would be the reduced computational time. In addition, for a triangular pattern, a 2-D model is nearly identical with a full 3-D model, as explained earlier, in the discussion of Figure 8, in the section on the simple model.

3-D, no fluid flow

We also considered using the 3-D model without the flow details of the salt stream. In these models, heat is radiated at an assumed uniform temperature from the outer diameter of the salt riser to the well casing. Obviously, during the first few months of operation, this is not the case. However, after about 3 months (based on previous models), the casing temperature comes up to about 500 C. Therefore if the inlet salt temperature is 550 C and the outlet is no more than 500C, then it is reasonable to assume that the pipe is radiating to the well casing at an average uniform temperature of 525 C. Due to the 4-year duration, the overall effects of this error are probably small. If a full 4-year simulation was run, the long-term temperature profiles could be compared to the 2-D full conjugate heat transfer model. However, this model was not run out to 4 years because it is still computer-intensive and a 2-D model is very adequate (see previous section argument).

2-D, no fluid flow

This model takes the same approach as the 3-D model without fluid flow (i.e., except for early time, modeling the heat transfer as uniform-temperature radiation from the outer surface of the molten-salt riser to the well casing is a reasonable approximation). While the 2-D approximation greatly eased the computational problem, there was still a problem. One of the scenarios that we wanted to model was diurnal solar heat input. The FEA code had a limitation of 5000 data points that could describe a time curve corresponding to the diurnal nature of using solar energy over a 4-year period. With a simple step function of 8 hours of solar input followed by 16 hours of night (average), this corresponds to 4 data points per day, or 1460 data points per year -- therefore the a full 4-year simulation could not be run (for some reason, a database restriction prevents re-reading the same data for each day). SRAC made a version with a 10,000 data point limit, allowing the full 4-year simulation to be possible. This model runs fairly quickly on a desktop computer.

Predictions of this model and the simple model for the diurnal case are compared in Figure 6. The simple model was run with a very high molten-salt flow rate in order to force the uniform temperature necessary for this comparison. The agreement is seen to be very reasonable.

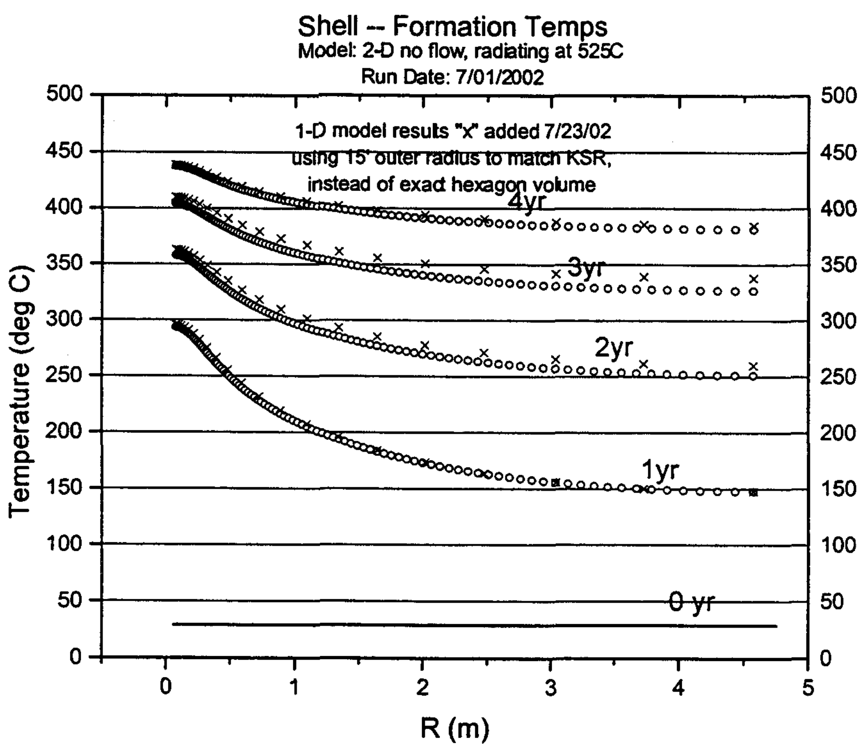


Figure 6. Comparison of results from FEA (circles) and simple model (Xs) for the case of uniform-temperature radiant source cycling diurnally to simulate solar input.

2-D, with fluid flow

This model describes the full conjugate heat transfer model, in 2-D. Conjugate heat transfer implies simultaneous solution of two analyses – the fluid heat transfer portion (molten-salt flow) and the conduction portion of the model (shale and overburden). Since fluid flow is involved, the run times are much longer. We had many problems with software support for the flow solver portion of the FEA code. We never were able to run the diurnal case. However, we were successful in running a constant input case. Finally, we were able to have the software developer run a 1-week diurnal case on their newer interface. The results looked reasonable and the temperature contours had the proper shape. A comparison of well-casing temperatures predicted by the FEA and simple models is shown in Figure 7.

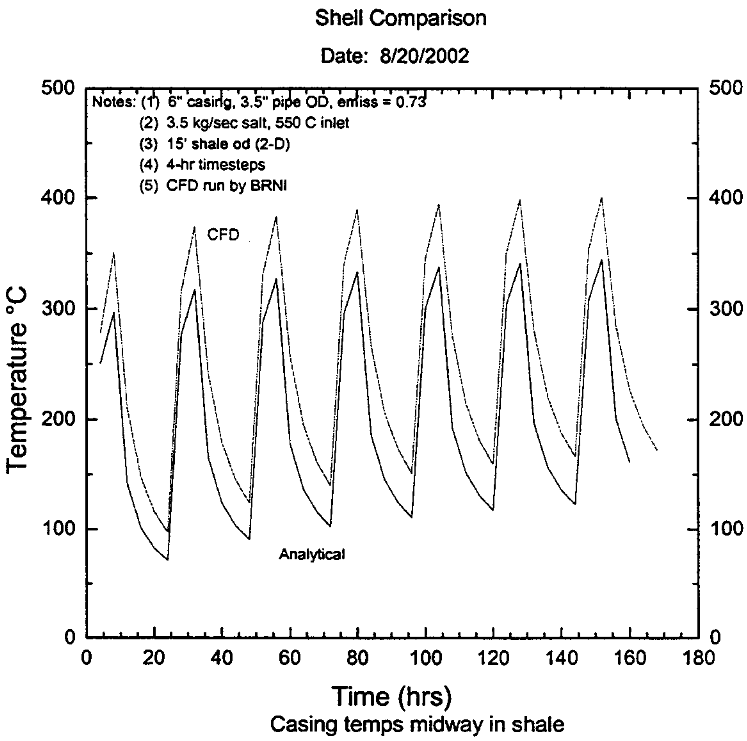


Figure 7. Comparison of predictions of well-casing temperature from FEA and simple models for the conjugate problem, with diurnal molten-salt heat input.

FEA/CFD Modeling Summary

The FEA/CFD models matched fairly well with the simple model. It was determined that a 2-D model is an excellent approximation of the 3-D for the chosen triangular pattern. The full conjugate heat transfer model could not run the diurnal case due to issues with the software developer. The FEA/CFD models validated the simple correlation-based models.

Since the simple models run quickly and are very easy to modify for a variety of scenarios, these models are used for the parametric studies.

3.2.3.4 Molten-salt parametric studies

These studies were run with the option of varying the mass flowrate to maintain the input power constant at 250 W/ft (6" casing) or 500 W/ft (12" casing). However, the mass flowrate was not allowed to exceed 3 kg/sec – an arbitrary but reasonable mass flowrate given the chosen pipe geometry. The 12" casing studies assumed a flux of 500 W/ft (double the 6" casing studies) because we saw no reason to incur additional expense without the benefit of increased power input.

The results are for a linear mapping space, i.e., the corners of the independent-variable space plus the center point. The four independent variables are:

- Overburden: 400, 1000' (baseline is 800')
- Shale depth: 300', 850' (baseline is 800')
- Pattern spacing: 20-40' (baseline is 30')
- Well casing: 6", 12" (baseline is 6")

Assumptions, constant parameters:

- Uniform shale properties
- Thermal mass of pipe neglected
- Conduction from shale to overburden neglected
- Heat flux target: 250 W/ft for 6" casing, 500 W/ft for 12" casing
    - Initial formation temperature: 50 °C (*see below)
    - Salt inlet temperature: 565 °C
    - Earth properties (from Shell):
        - conductivity = 1.4 W/m-K,
        - thermal diffusivity = 6.6×10^{-3} cm^2/sec
    - Pipe and casing properties:
        - steel conductivity = 22.5 W/m-K
        - insulation conductivity = 0.026 W/m-K,
        - emissivity = 0.73,
        - casing emissivity = 0.82
    - Pipe diameters (double these values for 12" casing studies)
        - D_1 = 1.38"
        - D_2 = 1.66"
        - D_3 = 1.995"
        - D_4 = 2.375"
        - D_5 = 2.992"
        - D_6 = 3.5"
        - D_7 = 4.0"
        - D_8 = 4.5"
        - D_9 = well casing ID (6" or 12")
    - Salt properties:
        - density = 1724 kg/m^3
        - specific heat = 1542 J/kg-K

  - dynamic viscosity = 0.0011 Pa-sec
  - conductivity = .551 W/m-K
  - Prandtl number = 3.08
- Maximum salt flow rate: 3.0 kg/sec
- Elements in axial direction: 100
- Elements in radial direction: 20 (non-uniform grid, fine near casing)
- Timestep: 8 hours

*We arbitrarily assumed 50 C initial shale temperature; subsequent discussion with Shell E&P indicates that 10 C is more typical. We estimate that the lower initial temperature will add about 15% to the time required to reach 325 C.

For a linear mapping space, the number of cases are $2^N + 1 = 17$. The case numbers and parameters are as follows:

Table 1. Molten-salt parametric study cases.

Case	Casing dia	Pattern	Overburden	Shale
1	6"	30'	800'	800'
2	6"	20'	400'	300'
3	6"	20'	400'	850'
4	6"	20'	1000'	300'
5	6"	20'	1000'	850'
6	6"	40'	400'	300'
7	6"	40'	400'	850'
8	6"	40'	1000'	300'
9	6"	40'	1000'	850'
10	12"	20'	400'	300'
11	12"	20'	400'	850'
12	12"	20'	1000'	300'
13	12"	20'	1000'	850'
14	12"	40'	400'	300'
15	12"	40'	400'	850'
16	12"	40'	1000'	300'
17	12"	40'	1000'	850'

The "stopping point" was determined by when the shale temperature reached 325 °C. Detailed results for each case are presented in APPENDIX G: MOLTEN SALT PARAMETRIC STUDY. These results are: (a) graphs of the vertical distribution of salt and casing temperature at the end of the simulation; (b) graphs of the time-dependent variations of the pattern peripheral temperature and the molten salt mass flow rate; (c) graphs of the radial distribution of temperature in the shale at the end of the simulation; and (d) pressure loss and pump power at the end of the simulation. Output variables of interest for each case are summarized in the following table.

Table 2. Molten salt parametric study results

Case	Time to Reach 325°C (months)	Initial Power (kW)	Casing Temp. (°C)	Overburden Temp. (°C)	Pump Power (kW)	Reservoir Energy (10^{12}J)	Shale Energy %
1	26	300	550	160	3.2	16.6	71.0
2	11	113	550	160	1.4	2.96	65.4
3	10	319	550	150	2.5	6.37	84.7
4	16	113	530	160	0.089	4.49	43.8
5	11	319	550	160	3.8	7.96	68.4
6	46	113	550	160	1.4	11.9	63.1
7	46	319	550	160	2.5	26.1	83.2
8	68	113	540	160	0.155	19.1	41.8
9	46	319	550	160	3.8	31.6	66.4
10	7	225	550	140	0.074	2.66	68.4
11	8	638	550	140	0.179	6.41	86.3
12	8	225	550	140	0.165	4.13	47.4
13	8	638	550	140	0.315	7.56	71.3
14	35	225	550	155	0.069	11.3	64.9
15	37	638	550	150	0.165	25.3	84.6
16	36	225	550	150	0.155	17.2	43.8
17	37	638	550	150	0.290	30.5	68.4

The shale thermal energy density falls in a narrow range between 0.68 and 0.74 GJ/m^3. The time to reach 325 °C can be correlated roughly by:

$$\text{time} = 0.02 \text{ month x } (D_2^2/D_1 \text{x1 ft}),$$

where D_2 is the injection-well spacing and D_1 is the casing diameter:

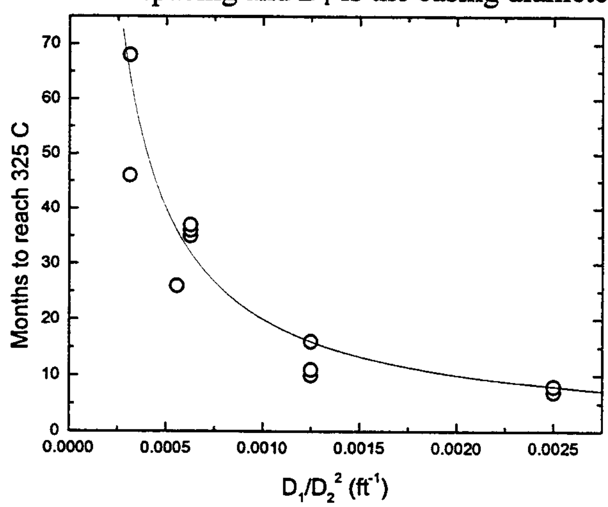


Figure 8. Molten salt predicted project times and their correlation.

The shale % of deposited energy is roughly correlated by:

$$\% = 100 - 30\sqrt{\xi},$$

where ξ is the ratio of overburden to shale thickness (Figure 9). Obviously, small values of this ratio are advantageous. One way to obtain small ratios is to directionally drill to form a "U-tube", consisting of a long horizontal run with a vertical bore to the surface at each end. Molten salt would enter through one vertical bore, and exit through the other. Since there would not be a counter-flowing stream, insulation would only be necessary in the overburden region of the vertical bores. A single pipe would be needed for the molten salt, with insulation mounted externally in the overburden region. There is an obvious tradeoff here, between the reduced cost of injection tubing and overburden losses, and the increased cost of directional drilling. We see no fundamental reason why molten salt could not be used in this way.

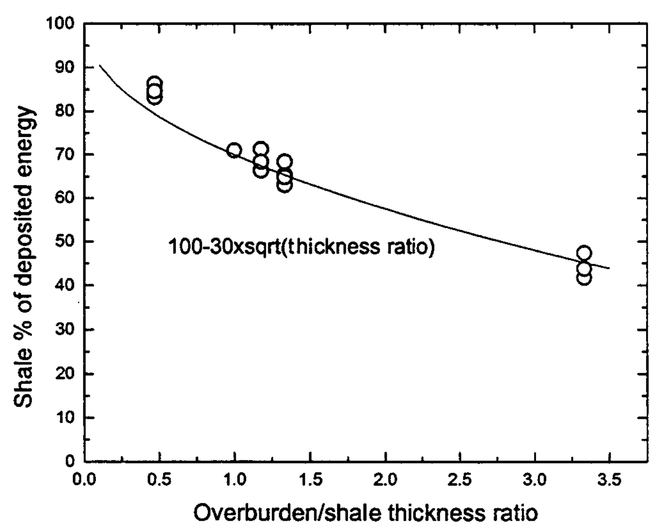


Figure 9. Molten shale predicted efficiencies and their correlation.

Note the pump power levels for the 6" casing studies were in the 1-4 kW range, with the exception of cases # 4 and #8. In these studies, the mass flow rate stayed very low to deliver the required power, whereas in the other studies, the mass flow rate increased to the maximum value of 3 kg/sec. For the 12" casing studies, pump power was very low because of the large pipe diameters.

Also note the power in the overburden is significant. The surface temperature (ignoring convective and radiation loss) is about 150 °C.

3.2.3.5 Additional molten-salt studies

Effect of shale inhomogeneity:

The simple model was used to explore several specific issues. The first was how a molten-salt system would respond to a stringer of low-conductivity shale. Using our baseline case, we set the thermal conductivity at the midlevel in the shale 30% below its nominal value, over a thickness of 32'. Figure 10 shows the predicted salt and casing temperatures early in the process (at 80 hours). Figure 11 shows the corresponding flux distribution. The effect is negligible in the salt and its pipes, and mild at the casing. Figure 12 shows the predicted salt and casing temperatures at the end of the process (at 18000 hours). The effect is even smaller at late time, because the flux is much lower then.

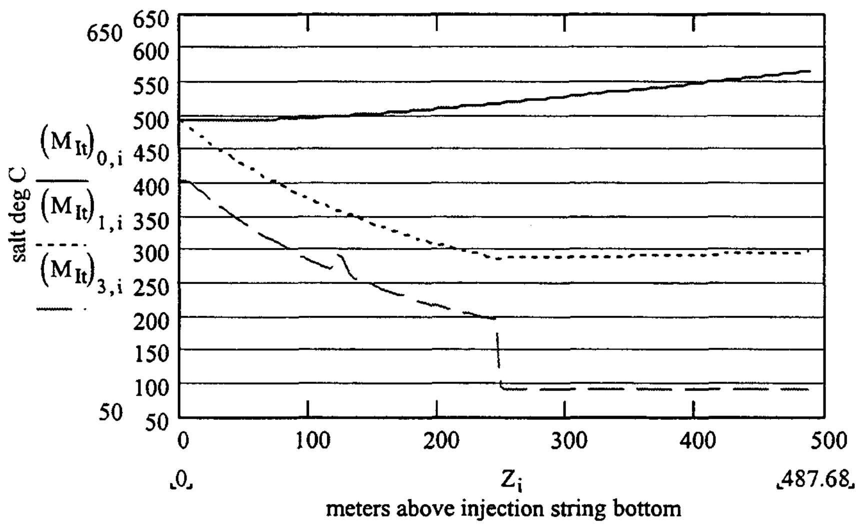


Figure 10. Baseline case 80-hour salt and casing temperatures with mid-depth 30% reduction in shale thermal conductivity over 32'.

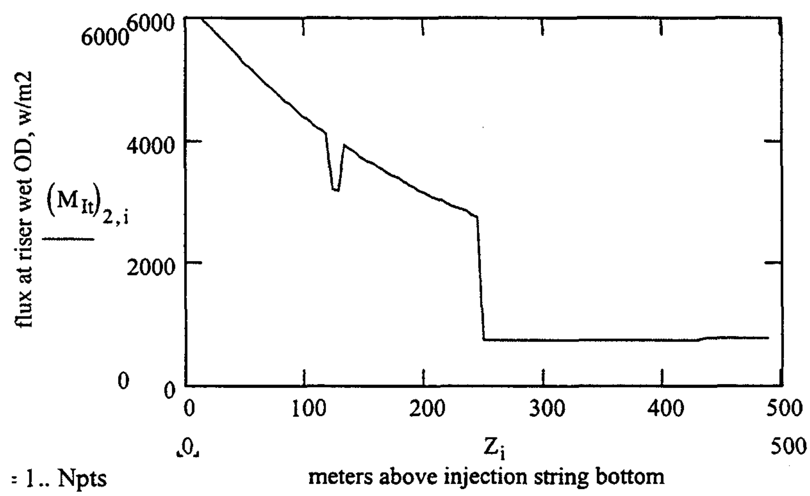


Figure 11. Baseline case 80-hour radial heat flux with mid-depth 30% reduction in shale thermal conductivity over 32'.

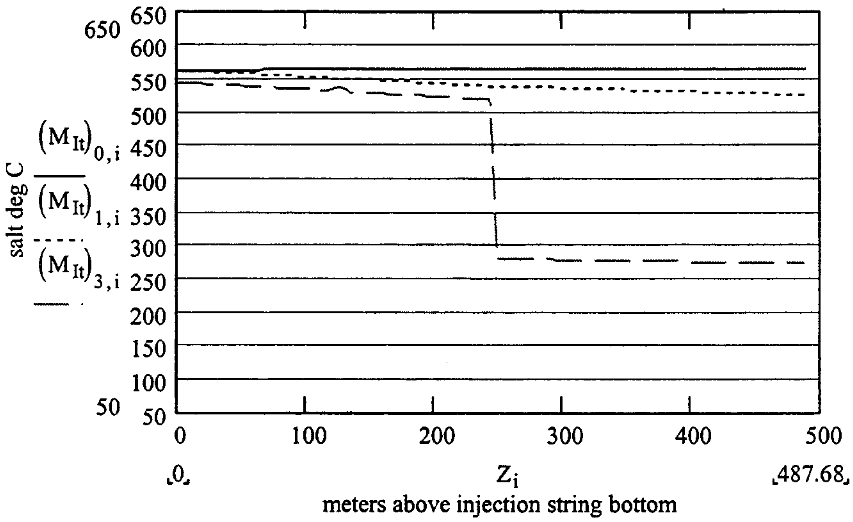


Figure 12. Baseline case 18000-hour salt and casing temperatures with mid-depth 30% reduction in shale thermal conductivity over 32'.

Heat extraction at project end:

Another issue we examined is molten-salt heat-extraction after a set of wells has been completely processed. For the baseline case geometry, we assumed initial uniform temperatures of 325C shale, and 200C overburden (these could be non-uniform if desired), and salt mass flow rate constant at 0.64 kg/sec, entering the string at 150C. The extracted heat is low grade: 190C initially, and 175C after two years. At two years, about 27% of the heat injected into the shale (and very little of the overburden share) has been extracted (Figures 13-15). A number of factors cause the extracted heat to be low grade, and the extraction rate to be slow. These include: the temperature difference required to drive the radiative heat transfer between the casing and injection string, and the relatively steep temperature gradients near the well bore, during injection, and to a lesser extent, during extraction. From a field management perspective, it might be difficult to input molten salt at temperatures as low as 150C for two years, so these estimates may be optimistic. On the other hand, there is a small region of high temperature adjacent to the well that we have neglected, that will add to the extracted power and its temperature.

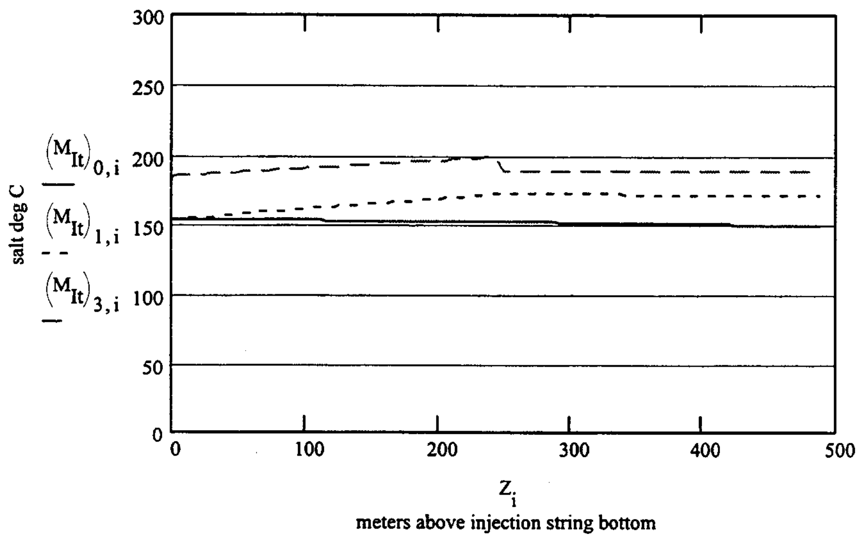


Figure 13. Casing, riser, and downcomer temperatures, after 2 years of heat extraction.

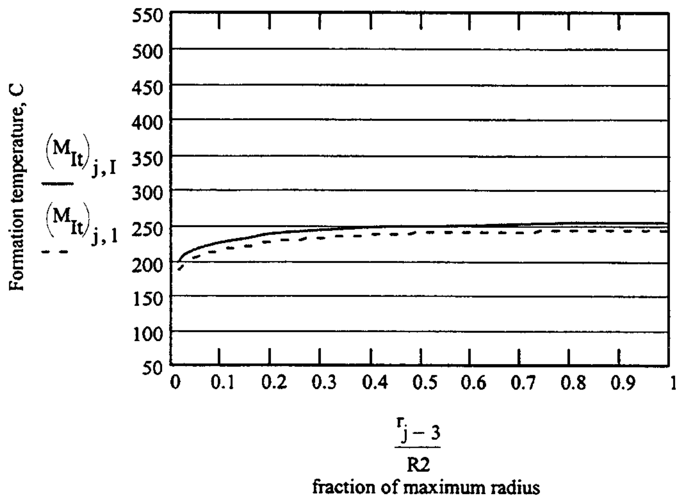


Figure 14. Shale temperatures vs radius, bottom & top of interval, after 2 years of heat extraction.

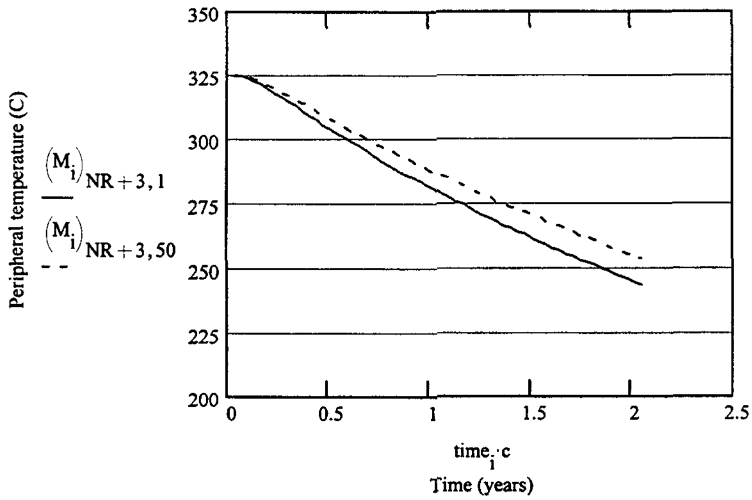


Figure 15. Shale temperatures during heat extraction, at maximum radius, bottom & top of interval, vs time.

<u>Field management</u>
For wells that are being heated, the salt exit temperature very quickly rises above the return temperature that is optimum for a solar plant. To counter this will require routing the salt through wells in series. This introduces additional questions about salt freezing, valving operations, and well heating rates. Our simple model can be used to develop effective field management strategies. Because our model runs very quickly, and is easily modified, it is able to simulate any proposed strategy. As an example, we modified our model to simulate 9 wells heated in series, for the baseline geometry (800' overburden, 800' shale, 6" casing, 30' pattern). Figure 16 shows the salt exit temperatures for the odd-numbered wells as a function of time. The behavior during the first year is an artifact of varying the mass flow rate to hold the deposited power constant for the first well. The very-low early-time temperatures pose a problem for controlling salt freezing. Perhaps this can be addressed with hydration and dehydration at individual wells. There are many other strategies for mass flow control and well sequencing that can be considered.

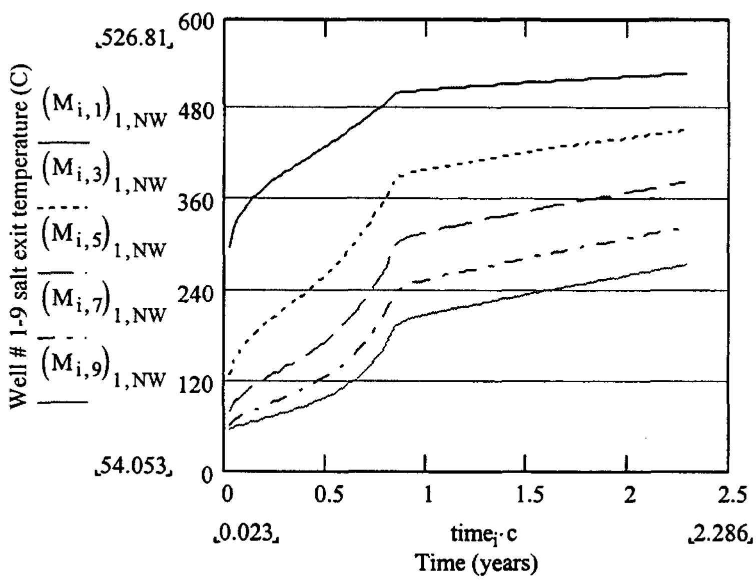


Figure 16. Simulation of molten salt exit temperatures for 9 wells in series.

3.3 DOWNHOLE STEAM

<u>3.3.1 Concept</u>

Downhole steam, like molten salt, belongs to the class of heaters that transport power as sensible heat. Downhole steam heaters have the following features:

1. Surface heat source -- this could be a fossil-fueled heater, a solar heater, or a hybrid heater (solar plus fossil fuel). It includes the distribution piping to carry the steam to the wells, and to return the steam to the source. A once-through system, with steam exhausted to the environment, is not considered. Such a system would be too wasteful, in terms of water resource, water conditioning, and thermal losses. In a closed system, steam exhausting from an individual well would at early times be condensed, but eventually would be too hot to condense. Vapor could be routed through additional wells until it was condensed, and then pumped up to pressure and through the heater. Alternatively, it could be returned to the heater as vapor, using a steam compressor. The former approach is chosen for consideration here, because it avoids the expense of compressing the vapor, and needs to pump only liquid.
2. Heat transfer fluid – steam at high pressure. As will be clear from the model results, high pressure is necessary to move the steam at the requisite flow rates through the considerable downhole piping lengths.
3. Downhole heater – as with molten salt, the steam needs to be ducted from the wellhead to the shale interval and back, delivering as much of its power as possible to the shale. Just as with molten salt, heat transfer between the downcomer and riser should be minimized, as should heat transfer to the overburden (heating the overburden would only be advantageous if the injection well were also a producer well, in which case, it could be used to prevent product condensation).

We envision the downhole system as simply an insulated injection string (downcomer). In the overburden interval, the casing would be insulated externally, to limit overburden losses. Since the downcomer insulation is between steam streams, it must be isolated from the steam to prevent steam intrusion. As with molten salt, high temperatures make commercial steam injection tubing unsuitable here. Threaded joints are feasible, but the risk of eventual leakage of steam into the insulation may dictate an all-welded system. The downcomer well head arrangement needs to accommodate substantial thermal expansion of inner pipe relative to the outer pipe. However, unlike molten salt, expansion joints for steam are feasible, so the downcomer can be supported by its outer pipe, as shown in Figure 17.

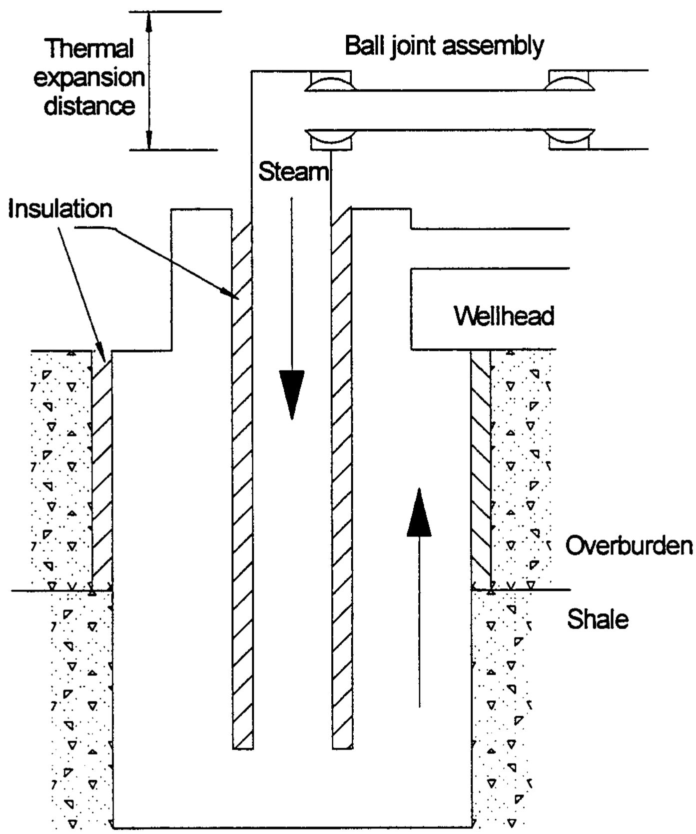


Figure 17. Steam insulated tubing and well head

3.3.2 Functional design

3.3.2.1 Materials

The insulated downcomer is the major component in the steam shale heater. It is envisioned as two concentric tubes, with insulation filling the annular space. In contrast with a molten salt system, corrosion should be less of an issue. The piping material can be any of the alloys typically used in modern steam superheat systems.

Just as with molten salt, the insulation needs to be high-temperature capable. All of the considerations discussed in section 3.2.2.1 apply here.

3.3.2.2 Structural analysis

For molten salt, the casing was considered outside the scope of this investigation, because the salt heater was entirely self-contained, and casing issues were expected to be dealt with by the existing electric-heating program. In the present case, steam introduces high pressures that will need to be contained. In our parametric studies, we considered 100-atm steam and a 12" casing. A 12" ID x 0.75" wall casing is just sufficient to contain 100-atm steam (conservatively neglecting external support by the surrounding geologic formation): the hoop stress is

$$12 \text{ x } 1 \text{ in}^2 \text{ x } 14.7 \text{ x } 100 \text{ psi}/1.5 \text{ in}^2 = 11760 \text{ psi},$$

just within the allowable stress at 600 C for type 316 stainless steel under the ASME Vessel Code, Section VII Division 1.

Our assumed 5.4" ID x 0.375" wall downcomer inside pipe is also within code requirements regarding steam pressure, with a hoop stress of 10580 psi. The downcomer outer pipe, 9" OD x 0.65" wall, can support a collapse pressure of

$$2.2 \text{ E } (t/D_{OD})^3 = 24000 \text{ psi},$$

far greater than 100 atm. The density of 600 C steam at 100 atm is only 1.56 lb/ft^3, so the hydrostatic pressure variation in 1600' well is only 17 psi.

The weight of the 1600' downcomer is 1.38×10^5 lbs. Viscous forces add at most

$$100 \text{ x } 14.7 \text{ psi x } (\pi/4) \text{ x } (5.4 \text{ in})^2 = 0.34 \times 10^5 \text{ lbs}.$$

Supported by its outer pipe, the resultant stress is a safe 9400 psi.

3.3.2.3 Costs

The main costs for a downhole steam heater are the insulated downcomer, any cost associated with the extra casing thickness required to contain the steam pressure, and the well head. We estimate that the cost of insulated string in the size considered here would be about $140/ft. The well head is a specialty item that will need to be costed. For present purposes, we estimate $50k. The wellhead and the downcomer for a 1600-ft. well total $224,000.

3.3.3 Performance analysis

3.3.3.1 Model

To predict the results of heating with steam, the simple correlation-based model written for molten-salt heating was extended to compressible flow. This did not affect the overall MathCad code structure, which still consists of two parts: (1) a quasi-steady thermo-hydraulic model for the steam flow and heat transfer within the well casing; and

(2) a transient-conduction model for the heat transfer in the shale and overburden zones. The geologic-formation transient-conduction part is unaffected by the change to steam. The thermo-hydraulic part must be changed for a number of reasons. First of all, now the energy equations in the downcomer and riser are coupled to the momentum equations, so all four must be solved simultaneously. A shooting technique is still appropriate, but now a pressure as well as a temperature must be guessed. The bottom-hole temperature and pressure are guessed, and sequentially corrected until the source temperature and pressure are obtained at the well head inlet. We also found that an implicit integration technique was necessary. With these changes, a robust algorithm was obtained.

3.3.3.2 Parametric studies

A major concern with steam is pressure loss, which can be seen as follows. The table below compares the thermo-hydraulic properties of steam and air with molten salt:

Table 3. Comparison of thermo-hydraulic properties.

600C, 100Bar	Steam	Air	Solar Salt (565C)
Cp (kJ/kg-K)	2.44	1.13	1.54
V (m^3/kg)	0.040	0.027	0.00058
k (W/m-K)	0.093	0.064	0.55
μ (10^5 Pa-s)	3.47	4.02	114
Pr	0.91	0.71	3.2

For a given ΔT between the inlet and exit streams, and a given heat delivery rate

$$Q = (Mdot)(Cp)(\Delta T),$$

the ratio of steam to salt mass flow rates is

$$Mdot_{steam}/Mdot_{salt} = Cp_{salt}/Cp_{steam} = 0.63,$$

and the ratio of Reynolds numbers is

$$0.63(\mu_{salt}/\mu_{steam}) = 20.7.$$

For this ratio of Reynolds numbers, the ratio of turbulent friction factors (f_{steam}/f_{salt}) is at least 1/3, and the ratio of steam to salt pressure increments in a given pipe is thus

$$\Delta P_{steam}/\Delta P_{salt} \sim (Mdot_{steam}/Mdot_{salt})^2(f_{steam}/f_{salt})(\rho_{salt}/\rho_{steam}) \geq 9.1.$$

The dominant ratio here is the ratio of densities. This result means that, for a given pipe size, a 200-psi molten salt pressure loss would become 1800 psi with steam, dictating the avoidance of the smaller pipe sizes and lower source pressures.

As in the molten salt studies, we varied the mass flow rate during a run, to try to maintain the input power constant. We scaled the target value as 125 W for each foot of overburden loss, and 250 W for each foot of shale. With the 12" casing only, we doubled these amounts for the 40' pattern spacing. Other assumptions:

- Uniform shale properties
- Thermal mass of pipe neglected
- Conduction from shale to overburden neglected
- Initial formation temperature: 50 °C (same comment here as with molten salt)
- Steam inlet temperature: 600 °C
- Steam inlet pressure 100 atmospheres
- Earth properties (from Shell):
    - conductivity = 1.4W/m-K
    - thermal diffusivity = 6.6×10^{-3} cm^2/sec
- Pipe and casing properties:
    - steel conductivity = 22.5 W/m-K
    - insulation conductivity = 0.026 W/m-K
- First pipe diameter set (D1,D2 = inner pipe, D3,D4 = outer pipe, D5-8 = casing)
    - D_1 = 2.992"
    - D_2 = 3.5"
    - D_3 = 4.276"
    - D_4 = 5"
    - D_5 = 6"
    - D_6 = 7"
    - D_7 = 7.8"
    - D_8 = 8"
- Second pipe diameter set (D1-4 x 1.8 of OTSI largest size, D5-8 = casing)
    - D_1 = 5.39"
    - D_2 = 6.3"
    - D_3 = 7.7"
    - D_4 = 9"
    - D_5 = 11.9"
    - D_6 = 11.91"
    - D_7 = 11.99"
    - D_8 = 12"
- Steam properties:
    - density = P/RT, R = 462 J/kg-K
    - specific heat = 2400 J/kg-K
    - dynamic viscosity = $3.8 \times 10^{-8} \times T/K$ Pa-sec
    - conductivity = .(-0.0235+0.0001375 x T/K) W/m-K
    - Prandtl number = 0.9
- Maximum steam flow rate: 3.0 kg/sec
- Elements in axial direction: 100
- Elements in radial direction: 20 (non-uniform grid, fine near casing)
- Timestep: 8-20 hours

For the first set of pipe diameters, the diameters D1-4 correspond to the inner and outer pipes of OTSI's largest insulated "thermal tube". The diameters D5-6 simulate a 6" ID casing. In the shale zone, the space from D6 to D8 is treated for convenience as steel, and has little effect on the solution. In the overburden zone, the space between D6 and D7 is made equivalent to a 1" radial gap with k = 0.026 W/m-K, by setting the conductivity artificially low. From D7 to D8 is modeled as steel. For the second set of pipe diameters, the scheme is similar.

The case numbers and parameters are as follows:

Table 4. Steam parametric study cases.

Case	Casing dia	Pattern	Overburden	Shale
1	6"	30'	800'	800'
2	6"	20'	400'	300'
3	6"	20'	400'	850'
4	6"	20'	1000'	300'
5	6"	20'	1000'	850'
6	6"	40'	400'	300'
7	6"	40'	400'	850'
8	6"	40'	1000'	300'
9	6"	40'	1000'	850'
10	12"	20'	400'	300'
11	12"	20'	400'	850'
12	12"	20'	1000'	300'
13	12"	20'	1000'	850'
14	12"	40'	400'	300'
15	12"	40'	400'	850'
16	12"	40'	1000'	300'
17	12"	40'	1000'	850'
18	12"	30'	800'	800'

Detailed results for each case are presented in APPENDIX H: STEAM PARAMETRIC STUDY. These results are: (a) graphs of the vertical distribution of steam and casing temperature, radial heat flux, and pressure at the end of the simulation; (b) graphs of the time-dependent variations of the pattern peripheral temperature and the steam mass flow rate; and (c) graphs of the radial distribution of temperature in the shale at the end of the simulation. Output variables of interest for each case are summarized in the following table.

Table 5. Steam parametric study results

Case	Time to Reach 325°C (months)	Initial Power (kW)	Overburden Temp. (°C)	Pressure Loss (atm)	Deposited Energy (10^{12}J)	Shale Energy %
1	22	300	120	42	14.5	82
2	9	125	120	18	2.54	78
3	11	263	120	32	6.37	92
4	7	200	120	32	3.02	61
5	10	338	120	48	7.20	81
6	36	125	120	18	9.79	75
7	41	263	120	32	24.0	90
8	34	200	120	32	13.5	55
9	38	338	120	48	27.2	77
10	9	125	230	0.3	2.9	75
11	12	263	230	0.5	8.0	90
12	8	200	220	0.6	4.0	56
13	11	338	225	?	9.1	79
14	30	250	260	0.3	11	70
15	33	525	260	0.5	27	88
16	30	400	255	0.6	16	49
17	32	675	250	0.8	32	74
18	22	300	250	0.7	17	79

We find that the shale thermal energy density falls in a relatively narrow range, from 0.69to 0.78 GJ/m^3, for cases 1-9, and 0.72 to 1.2 GJ/m^3 for cases 10-18. Although not as narrow a range as we saw with molten salt, this is striking, given the more than 10-fold variation in total energy deposited.

Cases 1-9, corresponding to a 6" casing, suffer serious pressure losses. In many cases, the exit pressure will not support the same flow rate through a second well in series with the first. Lowering the source pressure causes an even larger pressure drop. In some cases we found that the source pressure needed to be at least 90 atm. to support the flow through just one well. With a 12" casing, the pressure losses for a source at 100 atm. are minimal, and in fact, the source pressure can be reduced considerably before the losses become comparable to the source. Figure 18 shows the pressure distribution for case #18, with a source pressure of 15 atm, at 22 months. The pressure drop is only about 1/3 the source pressure. Figure 19 shows the shale temperatures at 22 months: they are not significantly different from the results at 100 atm. Thus, much lower pressures are possible with a 12" casing than with a 6" casing.

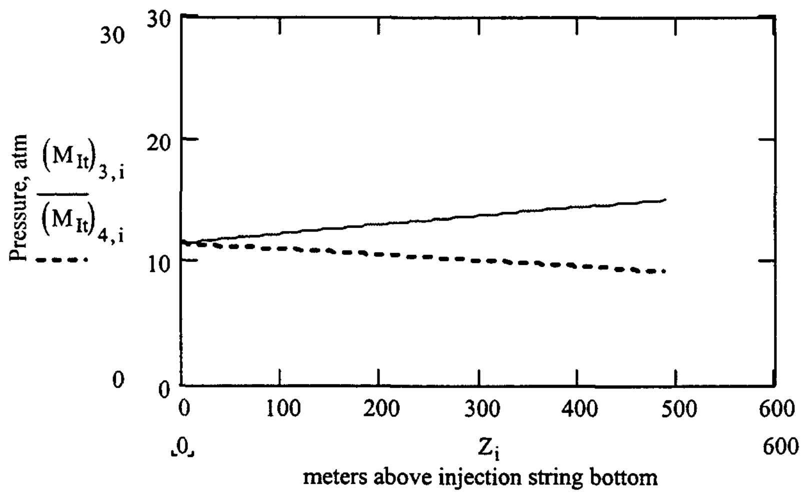


Figure 18. Case # 18 steam pressure distributions for a source pressure of 15 atm.

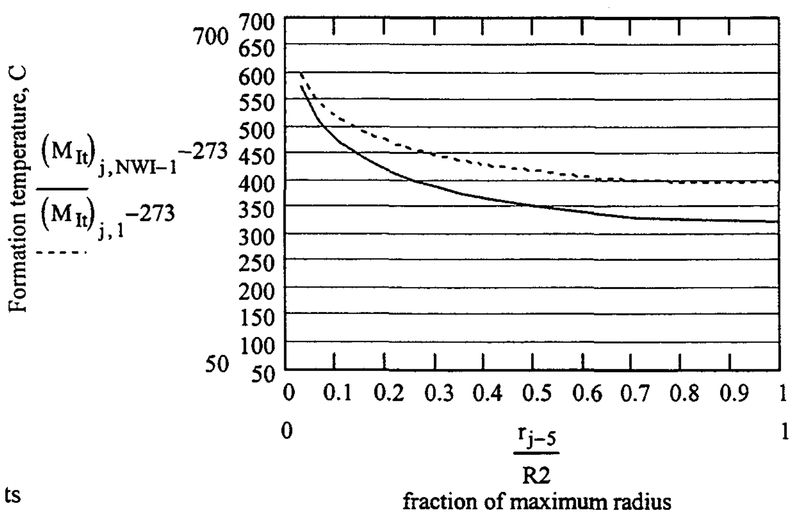


Figure 19. Case # 18 shale temperature distributions for a source pressure of 15 atm.

3.4 DOWNHOLE COMBUSTION

<u>3.4.1 Concept</u>

Downhole combustion differs fundamentally from molten-salt and steam heating of shale. Instead of transporting power from the surface to the shale as sensible heat, it is transported chemically, in the form of fuel. The conversion to sensible heat takes place adjacent to the shale. Moreover, the heat that is not deposited into the shale is recuperated at the top of the shale zone. Thus, neither the air and fuel supply streams nor the exhaust stream are hot, avoiding most of the thermal loss to the overburden that occurs with molten salt and steam, and negating the need for field-management considerations for wells in-series. Unlike chemical heat pipes, which have some of the same features and advantages, downhole combustion is a once-through (open loop) approach: air and fuel are compressed at the surface, and flue gas is exhausted to the environment. The possible role of solar power in downhole combustion systems is limited, at least in the short term, to providing electric power for ancillary equipment. In the long term, solar might be a candidate to supply synthetic fuel. Downhole combustion systems have the following features:

1. Surface equipment – a supply of fuel, along with pumps and/or compressors to circulate fuel and air downhole and a control system to safely operate the combustors.
2. Heat transfer fluid – flue gas. Low pressure is preferable, to minimize compression and pressure-recovery costs. This dictates a distributed combustor approach, as shown by the model results.
3. Downhole heater – this includes fuel and air supply lines, an exhaust line, combustors, igniters and control lines, and a recuperator. Heat transfer between the flue gas and the exhaust should be minimized.

We envision the downhole system built around an insulated exhaust riser centralized in the well casing. Riser insulation is only critical in the shale zone. In the overburden interval, it is of limited benefit, as is casing insulation, because of the recuperator. The riser insulation can be applied externally with no need for hermetic isolation, in contrast to steam and molten salt systems. Threaded joints are feasible. No special well-head arrangement is needed since there is no inner pipe – outer pipe thermal expansion issue.

To achieve a moderate flue gas temperature with a single combustor, considerable excess air is needed. A small fraction of the air is admitted to the combustion chamber. The rest is used to cool both the combustor and its flue-gas product. The large amount of excess air results in very-large compressor power costs. Our parametric studies show the limits of this approach. Another way to limit flue gas temperature is to use multiple small combustors spaced periodically from top to bottom of the shale zone. In place of large amounts of excess air, the shale itself cools the flue gas between each combustor. Our parametric studies illustrate the advantages of this approach. A conceptual drawing is presented in Figure 20.

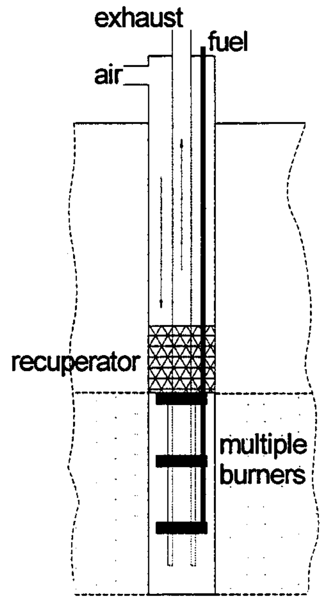


Figure 20. Downhole combustor concept.

3.4.2 Functional design

3.4.2.1 Materials

The major downhole items will be the riser and its insulation, the recuperator, the combustors, the igniters and their control lines, and the fuel supply line. Flame sensing, either integral to the igniters, or as separate devices, will also be needed. If electrical ignition is not feasible, pyrophorics such as tri-ethyl borane (TEB) are a possible alternative.

The riser can be assembled on site, using threaded joints and externally-applied and protectively-sheathed insulation. The fuel line would be medium-diameter tubing, with either welded or compression-fitting connections. Ordinary alloys capable of withstanding 600 C flue gas with excess air, are required. The possibility of fuel coking at riser temperatures (~500 C) would need to be assessed. Higher-temperature alloys may be needed in small quantities for parts of the combustors.

3.4.2.2 Structural analysis

For the downhole combustor hardware, no severe structural issues are apparent. This excludes the possibility of casing shear or collapse, which are not expected to be any more severe than in electric heating. The riser should easily be self-supporting, since, unlike the salt and steam systems, it does not have to support a second pipe, and there are no major differential thermal expansion issues.

3.4.2.3 Costs

The major downhole costs include the riser and its insulation, the recuperator, the combustors, the igniters and their control lines, and the fuel supply line. We estimate the cost of the insulated riser at \$70/ft, the fuel supply line at \$2/ft, the recuperator at \$30,000, the igniters at \$50 each, their control lines at \$10/ft, and the combustors at \$500 each. For a 1600' well with 25 combustors, this totals \$174,950.

3.4.3 Performance analysis

3.4.3.1 Model

To predict the results of heating with downhole combustors (DHCs), the simple correlation-based model written for steam heating was modified. The flow direction was reversed, and we added periodic point-releases of heat, and extended-surface enhancement of heat exchange between the two fluid streams (recuperation). This did not affect the overall MathCad code structure, which still consists of two parts: (1) a quasi-steady thermo-hydraulic model for the steam flow and heat transfer within the well casing; and (2) a transient-conduction model for the heat transfer in the shale and overburden zones. The geologic-formation transient-conduction part is unaffected by the change to DHCs. For the thermo-hydraulic part, we used the same shooting technique as with steam, except that, to avoid extreme sensitivity to initial conditions, the direction of integration was reversed to downward. The well exit temperature and pressure are guessed, and sequentially corrected until the two streams are at the same bottom-hole temperature and pressure. As with steam, we found that an implicit integration technique is necessary, and provides a robust numerical treatment.

For the compressor power, we assumed multi-stage centrifugal compressors, with a pressure-ratio limit of 3 per stage. We used standard expressions for the power per stage [18].

3.4.3.2 Downhole combustion parametric studies

We initially focused on a simple design that requires a single discrete combustor located at the overburden/shale interface. One advantage of this concept is that, except for the recuperator, the fuel and igniter control lines do not have to traverse hot zones. A disadvantage is the large amount of excess air that is required to cool all of the combustion products to a temperature that is safe for the casing (say, 650 C).

A simplified analysis illustrates the situation: imagine a number Nb of discreet burners, each with firing rate Q/Nb, where Q is the power required for the entire well. A small fraction of the total flow of air and combustion products is side-tracked through each burner for combustion purposes. The rest mixes with the burner combustion products to temper them to the safe (for the downhole hardware) temperature Tfm. Between burners, the flue gas cools, approaching the casing temperature Tc. Approximating the flue gas specific heat as equal to that of air, and neglecting the small additional mass of the fuel, the balance between combustion firing rate and flue gas cooling rate can be expressed:

$$\text{Mdot} = (Q/\text{Nb})/[\text{Cp}(\text{Tfm} - \text{Tc})]$$

Thus, for example, if Q = 200 kW, Nb = 1, Cp = 1 kJ/kg-K, Tc = 500 C, and Tfm = 600 C, then Mdot = 2 kg/sec. If the fuel is methane, with a lower heating value of 50,000 kJ/kg, the fuel flow rate is 4 g/sec. Stoichiometry requires 17.2 g of air for each gram of methane, or 68.8 g/sec. Thus, Mdot is 29 times the Stoichiometric amount!

We first ran our model for the single burner case. We focused on running at very-high pressure, to limit the frictional pipe losses. The problem with this approach is that extremely high compressor power is required, which can only be tolerated if the power is recovered from the high-pressure exhaust, using a turbine. This is not a realistic choice, because of the cost. We then ran at successively-lower source pressures, until the exhaust pressure was near atmospheric. This resulted in the lowest compressor power. We varied the air mass flow rate to be just high enough to limit the flue gas temperature to 600 C or thereabout. This means that the flow rate starts out at low multiples of Stoichiometric, but as the formation gets hotter, it must increase many times over. We ran the base case, which is case 1 in Table 6 (pg. 43). At the end of 33 months, the mass rate had nearly tripled (Figure 21).

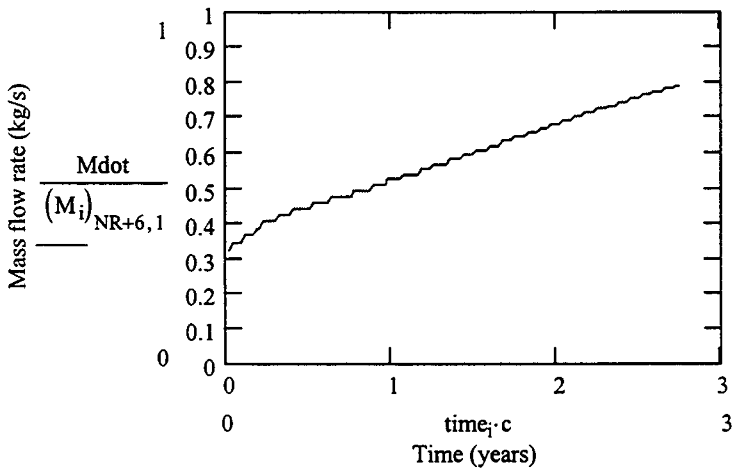


Figure 21. Mass flow rate; base case, single DHC.

The pressure loss at this time was nearly 2.5 atmospheres (Figure 22).

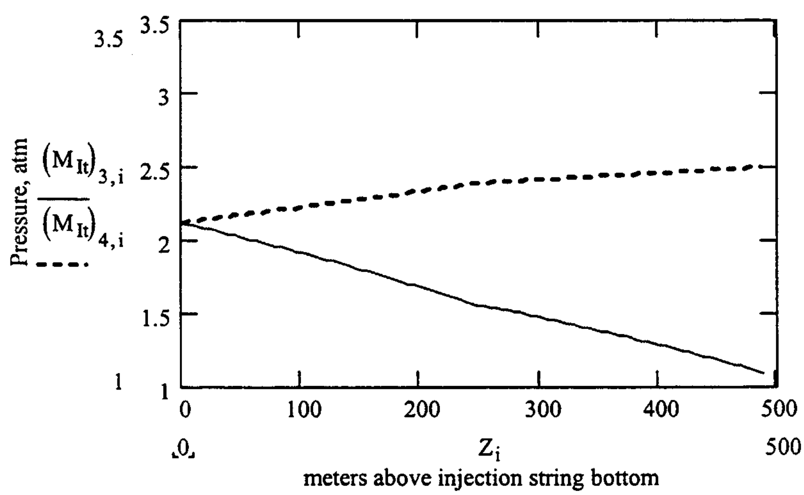


Figure 22. Air and flue gas pressure;, base case, single DHC, 33 months.

The compressor power had reached an unacceptable 120 kW (Figure 23).

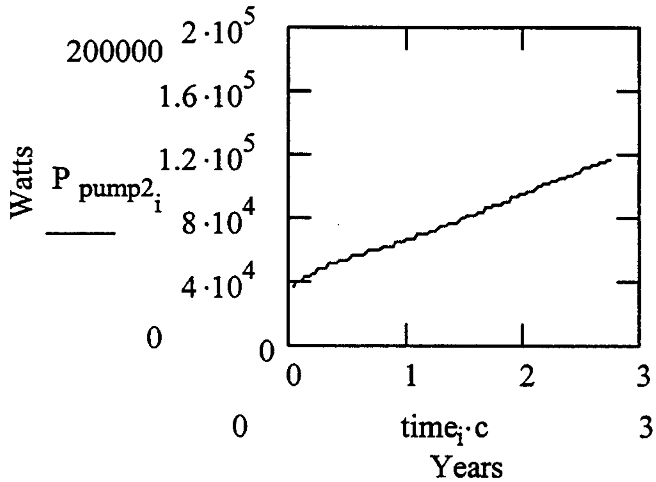


Figure 23. Compressor power; base case, single DHC.

The temperatures of the flue gas and the casing were still varying by more than 120 C over the depth of the shale (Figure 24).

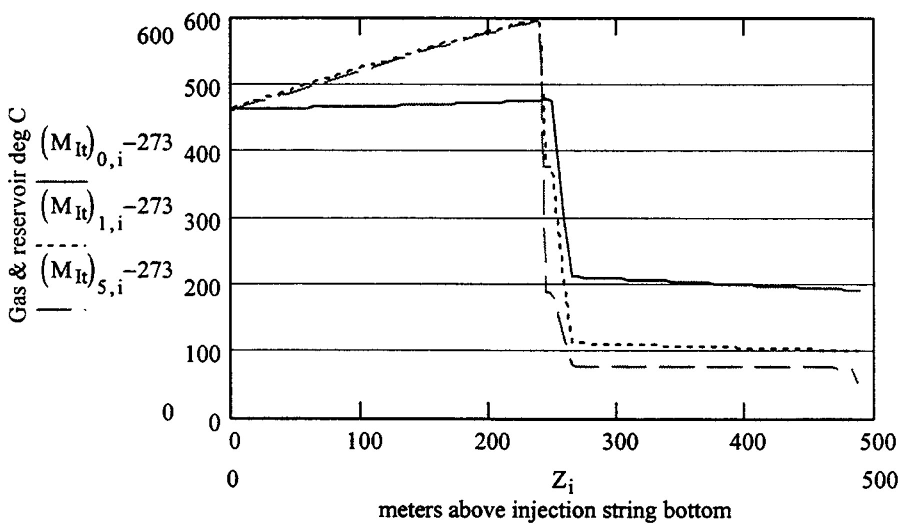


Figure 24. Temperature of air and flue gas (solid and dotted lines) and casing (dashed line); base case, single DHC.

The radial distribution of temperatures in the reservoir were widely spread between the top and bottom of the shale zone (Figure 25).

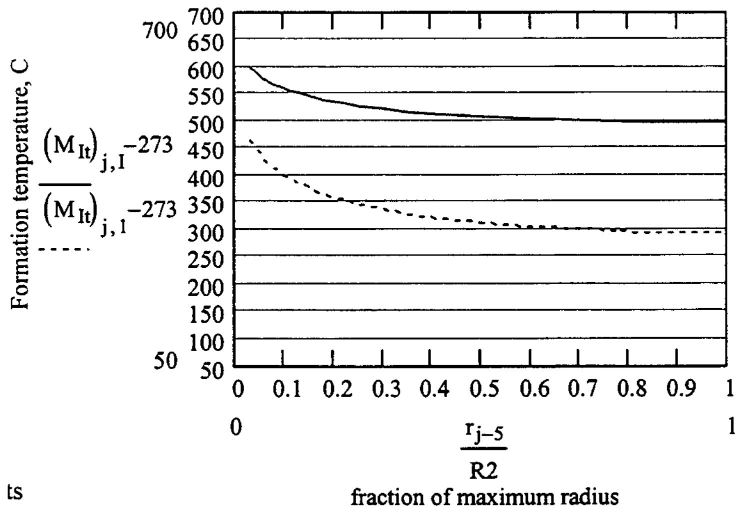


Figure 25. Temperature of the shale near its top (solid line) and bottom (dotted line); base case, single DHC.

These and many other similar results demonstrated that our concept for a single burner, or a few burners, is not feasible, and led us to consider large numbers of discrete burners (we modeled 1, 2, 3 10, and 25), or a single distributed burner.

For multiple burners, Mdot can be a small multiple of Stoichiometric. For example, with Nb = 25, Mdot is reduced to 29/25 = 1.16 x Stoichiometric. But there is another limit that must be considered: the mole fraction of oxygen available for the lowest burner in the well must be large enough to support combustion. For methane, the moles of oxygen consumed is twice the moles of methane:

$$CH_4 + 2Ns[O_2 + 3.76N_2] \rightarrow CO_2 + 2H_2O + 2Ns[(1\text{-}Ns^{-1})O_2 + 3.76N_2)$$

Note for later use that Ns = 1 is Stoichiometric, and that the number of moles of product equals the number of mole of reactant. If the air flow rate is Ns times Stoichiometric, and Nfdot is the fuel flow rate (all based on the total well requirement), then the rate of oxygen consumed up to the last burner is:

$$\text{Ncdot} = (\text{Nb-1}) \text{ x } 2 \text{ x Nfdot/Nb}$$

The rate of oxygen entering the well is Ns x 2 x Nfdot, so the rate reaching the last burner is this value minus Ncdot:

$$2 \text{ x Nfdot x}[\text{Ns} - (\text{Nb-1})/\text{Nb}]$$

For the last burner, the mole fraction of oxygen is this rate divided by the molar rate of all species, which is:

$$\text{Ntdot} = \text{Nfdot x (Nb-1)/Nb} + 2\text{Nfdot x Ns x } 4.76.$$

The final mole fraction of oxygen is thus:

$$X_{O2} = [1 - (Nb-1)/NsNb]/[4.76 + (Nb-1)/2NsNb]$$

For Nb = 25 and Ns = 3, the final mole fraction is 0.138. This means that with 25 burners, and 3 times Stoichiometric air, the last burner will receive combustion "air" containing 13.8% oxygen. For ordinary conditions, this would be considered at the lower limit to support combustion. If this is true as well at elevated temperature, then a small amount of air would need to be piped directly to the last several burners. The important result of this analysis is that multiple burners make it possible to run with much lower air flow rates (3 times Stoichiometric in this example, versus 29 times Stoichiometric with a single burner).

The remainder of the parametric studies were run with 25 burners. We assumed an input power of 250 Watts/foot, which corresponds to 200 kW for the baseline case of 800 foot of shale. Recall that the baseline molten-salt case was 300 kW, with the extra 50% provided for the losses into the overburden. Very little overburden loss occurs with the downhole combustor option.

The results are for a linear mapping space, i.e., the corners of the space plus the center point.

The three independent variables are:

- Overburden: 400, 1000' (baseline is 800')
- Shale depth: 300', 850' (baseline is 800')
- Pattern spacing: 20-40' (baseline is 30')

Casing size is not included as a variable here, because the lower range of casing size results in excessive pressure loss, and additionally, does not permit adequate space for the burners. We fixed the casing size at nominally 12".

Assumptions, constant parameters:

- Uniform shale properties
- Thermal mass of pipe neglected
- Vertical conduction from shale to overburden neglected
- Heat flux in overburden: 250 W/ft
- Initial formation temperature: 50 °C (same comment here as with molten salt)
- Maximum flue-gas temperature = 650 °C
- Recuperator length = 64 ft
- Recuperator surface enhancement: 10 x plain pipe
- Number of burners: 25
- Earth properties (from Shell):
    - conductivity = 1.4W/m-K,
    - thermal diffusivity = 6.6×10^{-3} cm^2/sec
- Pipe and casing properties:
    - steel conductivity = 22.5 W/m-K

- insulation conductivity = 0.026 W/m-K
- Pipe diameters (D1-4 scaled x 1.8 from OTSI largest size, D5-8 = casing)
  - D_1 = 5.386”
  - D_2 = 6.300”
  - D_3 = 7.697”
  - D_4 = 9.000”
  - D_5 = 11.90”
  - D_6 = 11.91”
  - D_7 = 11.99”
  - D_8 = 12.00”
- Flue gas properties (assume air):
  - Gas constant = 304 J/kg-K
  - density = ideal gas law
  - specific heat ratio = 1.368
  - dynamic viscosity = 0.9+0.0034*T/K {Pa-sec}
  - conductivity = $0.019+5.1\text{x}10^{-5}$*T/K {W/m-K}
- Elements in axial direction (dependent on shale depth): 50 elements in shale
- Elements in radial direction: 20 (non-uniform grid, fine near casing)
- Time step: 8 hours

The diameters D1-4 correspond to 1.8 x the diameters of the inner and outer pipes of OTSI's largest insulated “thermal tube”. The diameters D5-6 simulate a nominal 12” casing. In the shale zone, the space from D6 to D8 is treated for convenience as steel, and has little effect on the solution. In the overburden zone, the space between D6 and D7 is treated as insulated (0.4” radial gap, k = 0.026 W/m-K), and from D7 to D8 as steel.

For a linear mapping space, the number of cases are $2^N + 1 = 9$. The case numbers and parameters are as follows:

Table 6. Downhole combustion parametric studies cases

Case	Casing	Pattern	Overburden	Shale
1	12”	30’	800’	800’
2	12”	20’	400’	300’
3	12”	20’	400’	850’
4	12”	20’	1000’	300’
5	12”	20’	1000’	850’
6	12”	40’	400’	300’
7	12”	40’	400’	850’
8	12”	40’	1000’	300’
9	12”	40’	1000’	850’

The “stopping point” was determined by when the shale temperature reached 325 °C. Detailed results for each case are presented in APPENDIX I: DOWNHOLE COMBUSTION PARAMETRIC STUDY. These results are: (a) compressor power to supply the air at the assumed source pressure, and alternatively, needed to make up for the pipe losses, (b) graphs of the vertical distribution of flue gas and casing temperature, flue gas pressure, and heat flux at the end of the simulation; (c) graphs of the time-dependent variations of the pattern peripheral temperature and the air mass flow rate; (d) graphs of the radial distribution of temperature in the shale at the end of the simulation; and (e) calculations of deposited energy and energy balance at the end of the simulation. Output variables of interest for each case are summarized in the following table.

Table 7. Downhole combustion parametric studies results.

Case	Time to reach 325°C (months)	Initial Power (kW)	Reservoir Energy (10^{12}Joules)	Shale Energy %	Casing Temp. (°C)	Surface Temp. (°C)	Pump Power, (kW)
1	25	200	12.3	95.4	650	60	4.4
2	10	75	1.90	94.1	590	55	< 0.25
3	11	213	5.47	97.2	590	55	5.0
4	11	75	2.12	92.7	610	50	< 0.50
5	11	213	5.99	95.0	590	50	5.9
6	44	75	8.34	93.7	680	55	< 0.25
7	44	213	22.2	97.1	650	55	5.3
8	44	75	8.47	92.3	680	60	< 0.25
9	45	213	23.2	94.7	660	60	6.0

Again, we find that the shale thermal energy density falls in a narrow range, this time between 0.67 and 0.75 GJ/m^3 (for molten salt, it was between 0.68 and 0.74 GJ/m^3). As the above table indicates, the variation in time to reach 325 °C is strongly dependent on pattern size. In rough terms, the baseline case of a 30' spacing takes about two years to reach temperature, a 20' spacing takes about a year, and a 40' spacing takes slightly under 4 years. The power in the overburden is very small. The overburden surface (casing) temperatures changed little from the initial conditions. For this reason, we see no advantage to the directionally-drilled horizontal well bore approach (discussed for molten salt), in the case of downhole combustion.

Note the pump power levels are in the 4-6 kW range, except when the shale depth was shallow. In these studies, the mass flow rate was lower and therefore the associated pressure losses dropped off quickly. If a 6" casing was required, these power levels would increase significantly. For example, using the largest OTSI insulated pipe that would fit in a 6" casing, the hydraulic radii would be reduced by a factor of 1.8. Since the pressure gradient is inversely proportional to the cube of the hydraulic radius, one could expect the compression power to increase by approximately a factor of 6. Even if this was acceptable (for example for the shallower depths), the space available for combustors appears to be too small to accommodate the flame, cooling boundary layers, and excess-air bypass. A larger space could be created by constricting the riser at each combustor; the price would be the additional local pressure loss.

3.4.3.3 Additional downhole combustion studies

We used our simple model to explore an additional downhole combustion issue: how a DHC system would respond to a stringer of low-conductivity shale. Using our baseline case, we set the thermal conductivity at the midlevel in the shale 30% below its nominal value, over a thickness of 32'. Figure 26 shows the predicted flue-gas and casing temperatures early in the process (at 160 hours). Figure 27 is a magnified picture of these temperatures. Figure 28 shows the corresponding flux distribution. Figure 29 shows the magnified predicted gas and casing temperatures at the end of the process (at 18000 hours). The behavior is somewhat different than with molten salt, in that a low-conductivity stringer can cause an increase in the flue gas temperature. With molten salt, it only decreases the rate of cooling of the salt. This is because DHC heat transfer is driven by chemical heat release (although this is tempered by convection), whereas molten salt heat transfer is temperature driven. Thus DHC is intermediate between electric heating and sensible heating. Nevertheless, the effect is small for our downhole combustion concept.

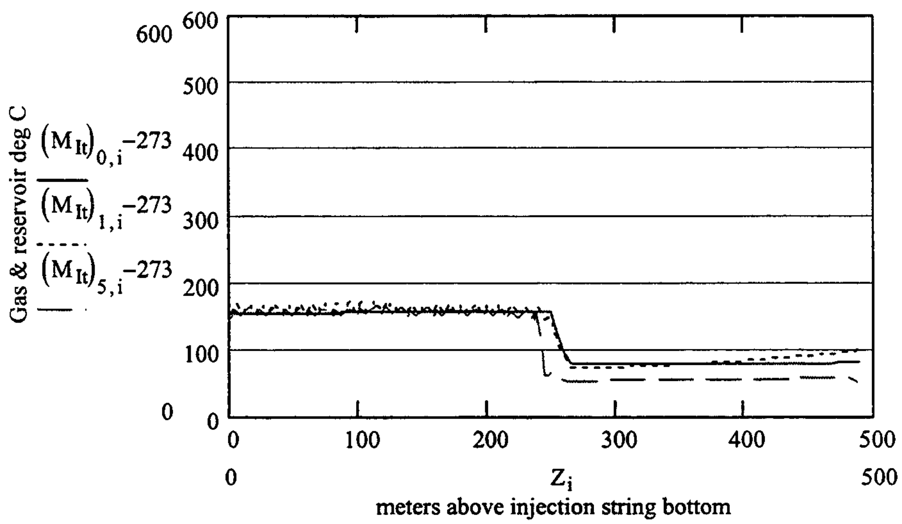


Figure 26. Baseline DHC case 160-hour flue gas and casing temperatures with mid-depth 30% reduction in shale thermal conductivity over 32'.

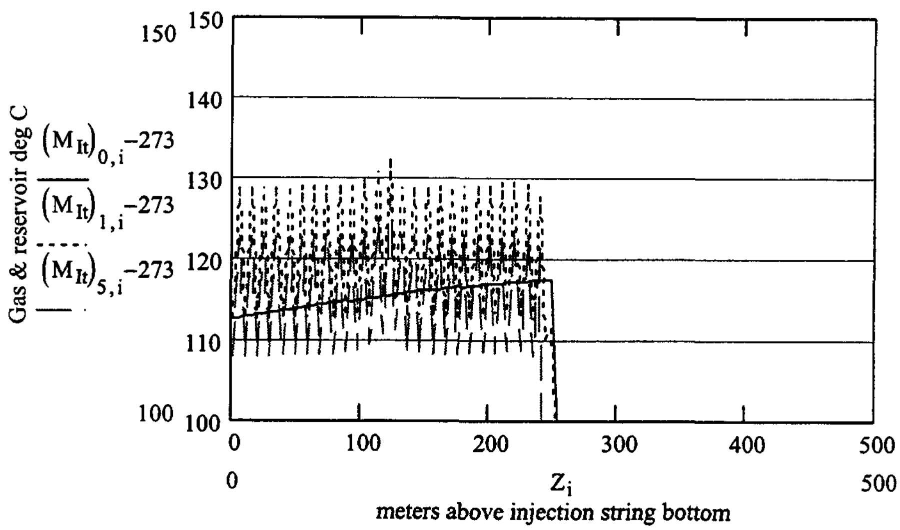


Figure 27. Baseline DHC case 160-hour magnified flue gas and casing temperatures with mid-depth 30% reduction in shale thermal conductivity over 32'.

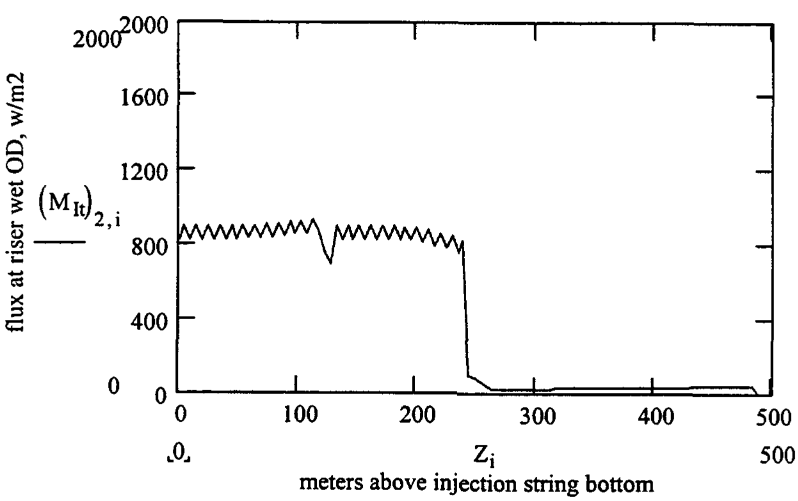


Figure 28. Baseline DHC case 160-hour flue radial fluxes with mid-depth 30% reduction in shale thermal conductivity over 32'.

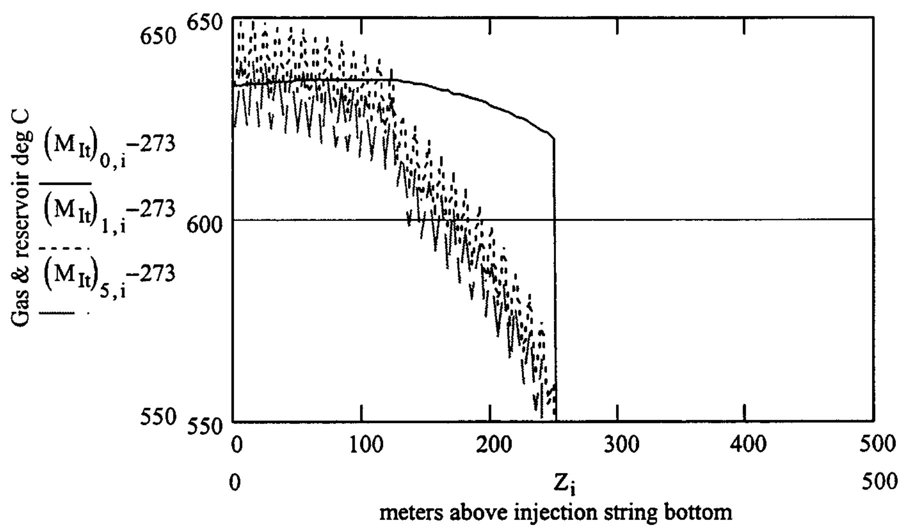


Figure 29. Baseline DHC case 18000-hour magnified flue gas and casing temperatures with mid-depth 30% reduction in shale thermal conductivity over 32'.

3.5 CHEMICAL HEAT PIPE

3.5.1 Concept

"Chemical heat pipe" refers to closed-cycle reforming/methanation (and similar) cycles [19]. In carbon dioxide reforming, methane and CO_2 are endothermically reformed to syngas (H_2 and CO) in a solar receiver, and exothermically methanated downhole. The high temperatures required for reforming, and large scale limit the solar application to central receivers. Instead of transporting power from the surface to the shale as sensible heat, this concept transports it chemically. The conversion to sensible heat takes place adjacent to the shale. Moreover, the heat that is not deposited into the shale is recuperated at the top of the shale zone, as is the waste heat at the solar receiver. Thus, neither the supply nor the exhaust streams are hot, avoiding most of the thermal losses that occur with molten salt and steam, not only within the overburden, but in the surface distribution piping. A very important difference from downhole combustors is that chemical heat pipes are closed loop, potentially emissions-free, and very suitable for utilizing solar thermal power. It would be practical to locate the solar plant hundreds of miles from the well field, if necessary. Downhole chemical heat pipe systems have the following features:

1. Surface equipment – a source of heat, a catalytic reforming reactor, a recuperator, and storage tanks, distribution piping and compressors to circulate the gases.
2. Heat transfer fluid – CH_4 and CO_2 would be used to initially charge the system.
3. Downhole heater – this includes supply and exhaust lines, a catalytic methanator, and a recuperator.

We envision the downhole system built around a syngas supply downcomer centralized in the well casing. The methanator catalyst could be continuously distributed or located at multiple discreet locations along the downcomer, within the shale zone. Issues of methanator design, flow control and reaction-product temperature will need to be addressed. Cycle performance will need to be optimized and verified. Solar-produced syngas cost was estimated in 1993 at 73.7 cents per therm [19]. Although improvements have been made since then, this remains a long-term option. A conceptual drawing is presented in Figure 2d.

3.5.2 Reaction chemistry

The choice of carbon dioxide or steam reforming for closed-cycle systems is at present unresolved. The cycles are:

Steam: $CO + 3H_2 \rightarrow CH_4 + H_2O$ (+206 kJ/mole)

Carbon dioxide: $CH_4 + CO_2 \rightarrow 2CO + 2H_2O$ (-247 kJ/mole)

Both have been demonstrated in solar closed cycles: the former with a ruthenium reforming catalyst and a nickel methanation catalyst; the latter with rhodium catalysts. Problems include catalyst stability, carbon deposition, and expense [19].

4. DISCUSSION

Overview

Of the heating methods considered, molten nitrate salt appears to be the best suited for near term application. Downhole combustion (DHC) has some very attractive features, but is a mid-term possibility, because of the amount of development that is required. Chemical heat pipes have many of the same attractions as DHC, and some added potential such as low emissions and solar compatibility, but are a long-term possibility, because they require significantly more development. Steam has some of the same features as molten salt, but with the added complications of high pressure required for flow in smaller well casings, condensation in wells during the initial stage of heating, and two-phase flow issues.

Molten nitrate salt

Molten nitrate salt has a long history in the chemical industry as well as in solar R&D. The behavior of materials at temperatures of interest has been well studied. For solar salt, the appropriate piping materials have been determined by an extensive combined effort of the USDOE and industry. Commercial fossil-fueled molten salt heaters exist, and molten-salt solar tower receivers have been designed, built, and tested in commercial settings. Thus, a variety of heat sources is possible, including fossil fuel, solar, and hybrid systems.

Our models indicate that good thermal efficiencies for shale heating with molten salt are possible, provided the overburden to shale thickness ratio is not too great. These efficiencies can be reached with insulated pipe similar in thermal performance to existing insulated steam injection pipe. Development will be required because of the higher temperatures in the present application. Our first-order analysis indicates that the structural issues are manageable. More sophisticated analysis, and testing will be needed to assess the effects of friction and buckling during the large thermal displacements expected within the insulated pipe. Some development will also be necessary for the rather specialized well head that will be needed, but no insurmountable obstacles are seen. A second possibility is that directionally-drilled "U-tubes" with long horizontal sections could be used to eliminate the need for insulated counter-flowing streams and reduce the overburden fraction. Finally, hydration/dehydration and/or trace heating strategies to prevent freezing will need to be analyzed and tested.

Molten-nitrate salt is expected to be one of the most robust methods of shale heating. This is a result of its simplicity and temperature-driven heat transfer. Our models indicate reasonable uniformity of heating, and little harmful effect of variations in shale thermal conductivity.

Of the three concepts considered here, we estimate the capital cost of molten salt downhole hardware to be the lowest. We used our cost and performance analyses to compare the economics of molten salt and electric heating. We estimated electric heater cost from commercial catalogs at $20k for 800' of shale, but instead chose to use Shell's actual near-term cost estimate of $37k. The results (APPENDIX J: ECONOMIC COMPARISON OF MOLTEN SALT AND ELECRIC HEATING) indicate a very-small cost advantage (0.4%) for molten-salt heating for a standard case of 800' overburden, 800' shale, 40' pattern spacing, 2.7¢ per kWe, and 27¢ per therm natural gas. A sensitivity analysis shows the molten salt advantage increasing to ~25% for a number of other scenarios, including halving the overburden and increasing the cost of electricity by 1¢.

In our judgment, molten-nitrate salt heating is a good candidate for near-term use.

<u>Steam</u>

Heating with steam has some of the same attributes as using molten-nitrate salt: it is delivers the heat primarily as sensible heat, and the heat transfer is temperature-driven. Our modeling suggests similar thermal performance. It contrasts most sharply with molten salt in materials compatibility and hydraulic behavior. Its lower density results in larger pressure losses, which limit the pipe sizes that are practical. Condensation will occur in each well during the early stages of heating, and must occur in one or more wells at all times in order to pump liquid back to the boiler. Pumping liquid out of wells, and two-phase flow at other points, will complicate operations.

<u>Downhole combustors</u>

Downhole combustion avoids nearly all losses to the overburden. Our modeling suggests that good uniformity of heating and very low air-pumping costs can be achieved with multiple discrete distributed burners.

It would be very difficult to adapt downhole combustion to a solar heat source (solar synthesized fuel is a long-term possibility). The most likely fuel would be on-site product, but for a considerable initial time, until the product stream is established, fuel would have to be brought in from elsewhere. It is also likely that on-site product would have to be supplemented, based on shale compositions provided by Shell E&P.

There is some existing expertise in downhole combustors, stemming from the work on downhole steam generators of 20 years ago. Nevertheless, considerable development will be necessary, in design and testing of combustors, igniters and controls. The temperatures required here are much higher than with downhole steam generators, and water cooling is not an attractive option.

Our model indicates that heating should be reasonably uniform, and shale thermal conductivity variations should have little impact on the hardware. Downhole combustors are expected to be less robust than molten-nitrate salt heaters, because of sensitive downhole components such as nozzles, cables, and igniters. Some of these components might be avoided by using pyrophorics for ignition.

Downhole combustors require significant development, especially to ensure long life and reliability, and therefore should be regarded as a mid-term option.

5. RECOMMENDATIONS

Our technical and economic analysis indicates that shale heating with molten-nitrate salt is a good near-term option. Some development will be required before deployment, including:

1. Design and testing of insulated pipe for 565 C solar salt.
2. Design and testing of a special well head engineered to accommodate the insulated string.
3. Adaptation and testing of existing commercial molten-salt hydration/dehydration equipment and electrical heating techniques for freezing prevention.
4. Analysis to optimize hardware, systems operation, and field management strategies (using simple models such as are presented herein).

APPENDIX A: STATEMENT OF WORK
CRADA No. SC02/01646
December 12, 2001

Methods and Energy Sources
for Heating Subsurface Geologic Formations

A. PURPOSE

The purpose of this collaboration between Sandia National Laboratories (Sandia) and Shell Exploration and Production Company (Shell) is to evaluate a number of methods for delivering heat to oil-producing geologic formations and to evaluate the potential benefits of using solar thermal energy to heat the subsurface at a proposed commercial oil shale site in Northwestern Colorado.

Reasons for Cooperation

As the lead laboratory for the Department of Energy's Concentrating Solar Power program, Sandia designs, develops, models, fields, tests, and evaluates solar components and systems. Sandia also has extensive capabilities in designing, modeling, and testing heat transfer systems, as well as in the fields of metallurgy, drilling research, and field testing (some specifically in oil shale). Sandia will draw upon its expertise to utilize known solar processes and equipment to design systems to perform solar heating of oil shale. Shell brings a wealth of knowledge and expertise in the oil industry, including geologic modeling, drilling, and oil exploration and processing. Working cooperatively, Shell and Sandia will explore new heat delivery options and the benefits of integrating a solar thermal system as the heat source for the heat delivery system.

<u>Public Abstract</u>

Sandia National Laboratories and Shell Exploration and Production Company will jointly evaluate a number of methods for delivering heat to oil-producing geologic formations. In the current effort, the parties will evaluate various heat delivery systems for pyrolysis of oil shale and evaluate the potential benefits of using solar thermal energy to heat the subsurface at an oil shale site in Colorado.

B. SCOPE

Technical Objectives

The goals of this project are to:

- Evaluate and compare heat delivery systems for pyrolysis of oil shale
- Evaluate the potential benefits of using solar thermal energy to heat the subsurface at a proposed commercial oil shale site in Northwestern Colorado.

<u>Phases of the Project</u>

There are no phases associated with this project.

Tasks and Division of Responsibilities

Task No.	Task Description	Duration (months)	Responsible Parties
1	Compare various heat delivery systems for pyrolysis of oil shale	01–10	Sandia/Shell
2	Evaluate potential benefits of using solar thermal energy at a Colorado oil shale site	01–10	Sandia/Shell
3	Prepare final report	10–12	Sandia/Shell

Task Descriptions

Task 1: Compare various heat delivery systems for pyrolysis of oil shale

Discussion. Sandia will evaluate several alternative approaches for delivering thermal energy at reasonable rates to the subsurface. Shell's modeling of oil shale formations will provide input to Sandia's evaluation of heat delivery systems. The following four different heat delivery systems will be evaluated:

1. Electric resistance heating
2. Heating using molten nitrate salt
3. Heating using steam
4. Downhole combustors

Sandia will perform a high-level systems modeling and evaluation of these various options. Major design parameters to be considered include the following:

- Selection of the heat delivery medium (e.g. radiation from electric heater, heating using salt, steam, combustion gas, etc.)
- Design of the downhole heater (e.g. electric heater, circulating salt, circulating steam, heat pipe, combustor, etc.)
- Materials issues
- Overburden insulation considerations
- Layout pattern of the wells (e.g. vertical, horizontal, spacing, depth)

Deliverable. Report that evaluates and compares each heat delivery system.

Task 2: Evaluate potential benefits of using solar thermal energy at a Colorado oil shale site

Discussion. Sandia will evaluate the use of solar thermal energy to heat the subsurface at Shell's Northwest Colorado site. Shell's knowledge of drilling and site conditions will guide Sandia's evaluation of the use of solar thermal energy. The evaluation will be structured so that it can be modified to obtain results from other sites that have different solar resources, site conditions, and geologic profiles.

The evaluation will include the following issues:

- Role of solar energy, including environmental and energy advantages in retorting shale
- Readiness of technology (with input from Task 1 results)
- Potential sources of industrial support
- Specific site characteristics based on satellite data and geographical information for solar radiation
- Modeling of the oil shale thermal behavior and the coupling of the solar and heat delivery systems (from Task 1)
- Economic/environmental benefits of solar energy (compared to electric and fossil-fired systems)

The study will include an evaluation of the use of solar energy with any of the heat delivery systems (e.g. substituting solar thermal energy for the fossil fuel-fired salt or steam system).

Deliverable. Report that summarizes the potential for using solar energy to heat the subsurface at Shell's oil shale site.

Task 3: Prepare final report

Discussion. Sandia and Shell will prepare the final documentation required to close out the CRADA, including DOE reporting requirements.

Deliverables. Final CRADA closeout documents.

APPENDIX B: 3/12/02 VU GRAPHS

Methods & Sources for Subsurface Heating

Kickoff Meeting

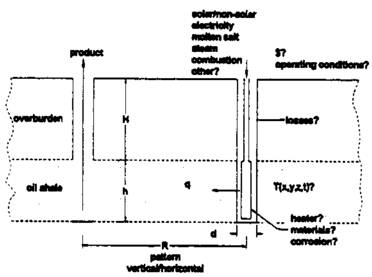
March 12, 2002

Craig Tyner
Scott Jones
Scott Rawlinson
Jim Moreno

Presentation Outline

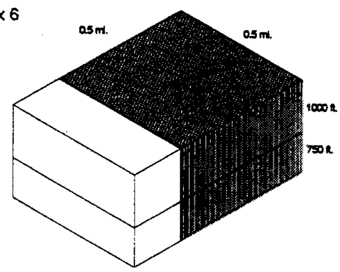
- Overview of Downhole Concepts (Task 1)
  - Task 1 Definition
  - Top level issues
  - Concepts under consideration
- Solar Integration with Downhole Concepts (Task 2)
- Downhole Concepts Issues, Analysis
- Discussion
  - Sandia questions
  - Shell feedback

Downhole Concepts Task Definition



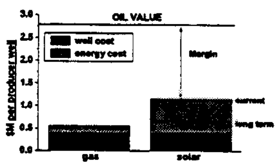
Issues Discussion: Baseline Case

- [¼ mi.^{2} x 4 yrs] x 6
- 7-spot patterns
- 5790 injectors
- 2895 producers
- R = 30 ft.
- d = 6 in.
- q = 250 W/ft



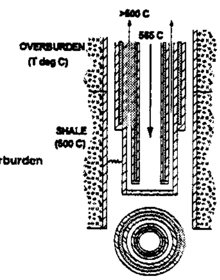
Issue: Profit Margin Sensitivity

- van Meurs et al patent – Example 2
  - 42 bbl/well/d x 9y @ $20/bbl
  - 3 wells x 1750 ft @ $75/ft
  - 10.55 MMBtu/well/day x 2 wells x 9y @ $2.50/MMBtu gas
  - 20.3 MkWh$_e$ @ $0.038/kWh, solar (current)
- Points to address
  - Sensitivity to losses
  - Impact of resource on cost
  - Sensitivity to other costs



Issue: Heat-Transfer Fluid Overburden Losses

- Loss $_{overburden}$ < Loss $_{electric\ conversion}$?
- Assume:
  - Baseline-case dimensions
  - 565C heat-transfer fluid at surface
  - 500 C @ shale-interval well casing
  - OTSI Thermal Tube 3-H equivalent
    - 0.015 Bruhn-8-F, full joint
    - Requires development for this application
- Limited model result: 33% loss to overburden
- Points to address:
  - Complete the present loss model
  - Tubing development required
  - Additional losses above ground



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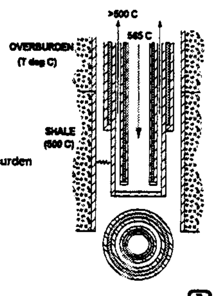
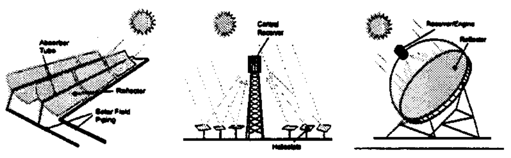


Approach to Task 2

- Goal is heating oil shale, not necessarily using solar energy
  - Let down-hole concepts drive analysis
- Start w/ broad look at options (Today)
  - CSP overview
  - Assume current system designs
  - Include other renewable technologies as benchmarks
  - Get feedback from Shell
- Discuss next steps

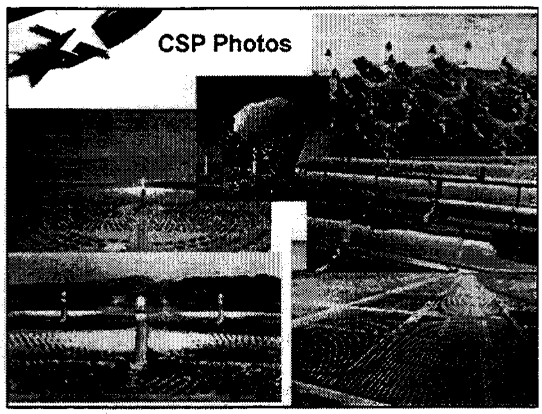
CSP overview

CSP Technology	Size	Status	Fluid	Oper. Temp.
Trough	10-200 MWe	354 MWe Commercial	Synth Oil	390C / 735F
Tower	30-200 MWe	10 MWe Demo	Molten Salt	565C / 1050F
Dish/Stirling	10-25 kWe each	Prototypes	Engine-H,He	800C / 1475F



Parabolic Troughs Power Towers Parabolic Dishes

CSP Photos



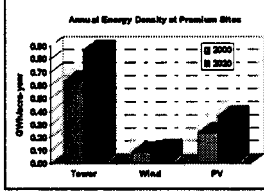
Renewable Sources vs. Down-hole concepts

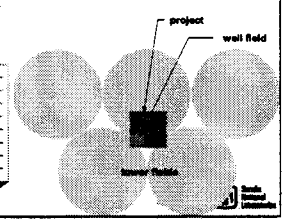
- 0th-order costs
  - Based on current system configurations (not always appropriate)
  - Assumes premium sites
  - Corporate finance (~10% nominal FCR)
  - Aggressive technology development through 2020 (DOE est.)

Technology	Electric resistance cents/kWh$_e$		Heat Transfer Fluid (Salt, Steam) cents/kWh$_t$		Comb gas	Chemical heat pipe
	current	2020	current	2020		
CSP	12	3.8	3.8	1.3	-	yes
Photovoltaics	35	7	38.9	7.8	-	-
Wind	4.5	2.5	5.3	2.9	-	-

Land Requirements

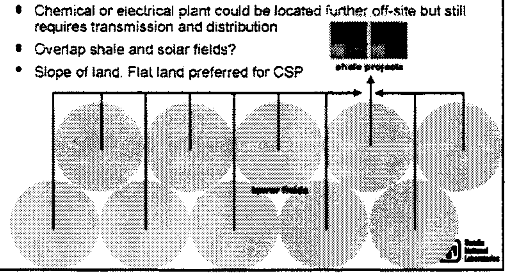
- Shell base case energy density
  - 1.1 GW$_t$ x 24 hours x 365 days on 160 acres = 60 GWh$_t$/acre-year
  - Total project size 1.25 x 1.25 miles over 24 years (6.25x larger)
- CSP better than competition, more diffuse than shale field
  - Tower plant land is 15x larger (60/0.64/6.25) than total field size
  - Other CSP technologies up to 2x smaller



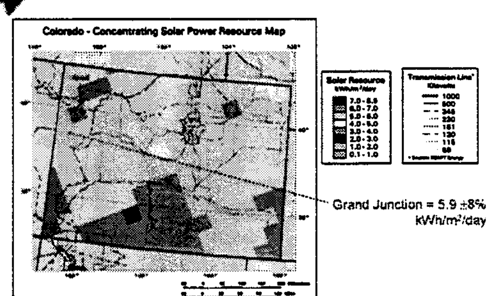


Addressing Land Requirements

- Other cases in patent require lower energy density
  - Helpful to have range defined
- Chemical or electrical plant could be located further off-site but still requires transmission and distribution
- Overlap shale and solar fields?
- Slope of land. Flat land preferred for CSP



Solar Resource



Next Steps

- Eliminate unlikely options
- Obtain better resource and geographical data
- Develop concepts for integration with down-hole technology
  - Shale field management (sequencing, geometry, preheating, etc.)
  - Materials issues
- Model interaction with subsurface
- Develop price and performance estimates
- Update analysis
- Further down-select and refine concepts

Downhole Concepts Approach

- Formulate basic heat delivery concepts
- Identify major issues
- Analyze to address issues
- Refine concepts
- Evaluate concepts
- Iterate with Shell
- Final Report

Evaluation Methodology

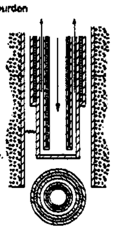
- Heat transfer parametric study
  - Overburden and pattern considerations
  - Formation and equipment temperatures
  - Volume % heated above carbonate decomposition temperature
  - Efficiency
  - Heat delivery control requirements
- Estimate capital cost
  - Major items
- Estimate operating cost
  - Fuel, if required
  - O & M
- Assess lifetime
  - Corrosion issues
  - Thermal fatigue
  - Seals

Solar and general issues,analysis

- Concept: diurnal heating
- Issue
  - requires instantaneous rates 3 - 4 X constant-heating rate → higher temperatures
  - or storage (trade off moderate cost against diurnal complications)
- Points to address
  - How are temperatures affected?
  - Formation temperatures?
  - Casing temperature?
- Additional points
  - Overnight temperatures, longer shutdowns?
  - Include pyrolysis, coking, carbonate decomposition, other, in model?
  - Shell modeling help?
  - What patterns, plots, sizes, and formations should be considered?
- Progress: casing-to-formation constant-rate heating model validated; diurnal cases underway

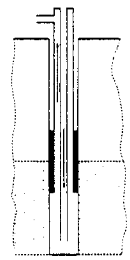
Solar & general

- Concept: delivery via heat transfer fluid (HTF)
- Issue: surface, overburden and stream to stream losses
  - Requires insulation between streams, and between streams and overburden
- Issue; solar receiver HTF return temperature
- Points to address:
  - Calculate losses
  - For commercial downhole thermal tubing & standard surface piping
  - As a function of temperature
  - Diurnal and constant cases
  - Formulate thermal tubing concept for 600 C (750 C?)
  - Field management study (sequence/timing) to control HTF return temp.
- Progress: string-to-casing heat-transfer model is running



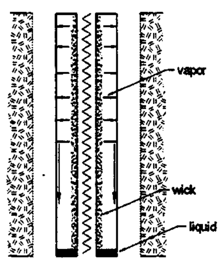
Solar & general

- Concept: delivery via heat transfer fluid directly to casing
- Issues
  - eliminates some pipe
  - does not eliminate insulation
  - requires a high-temperature packer
- Points to address
  - Packer temperature limits < 550 F?
  - At this point, any reason to pursue?



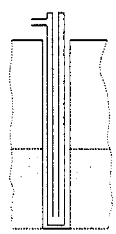
Electric heating issues, analysis

- Shell concept:
  - Heater details?
- Issues?
- Points to address:
  - Would heat pipe help heater life?
  - Heat pipe cost vs heater replacements?
  - Other? (depends on issues)
- Heat Pipes
  - Two-phase, nearly isothermal
  - Sandia has extensive experience in heat pipe design and testing, up to 100KW, and 800C



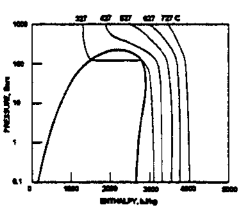
Molten-salt heating issues, analysis

- Concept
  - Seals & carbon steel not permitted
  - Self contained insulated tube in tube
  - Add distributed injection if needed for uniformity
- Issues
  - Uniformity of flux distribution
  - Preheat requirements
- Points to address
  - Calculate heat flux distribution, formation response
  - Determine preheat method, calculate response
  - Calculate early-time overnight temperatures
  - Calculate early-time outage temperatures
- Progress: string-to-casing and casing-to-formation heat transfer models are being coupled



Steam issues, analysis

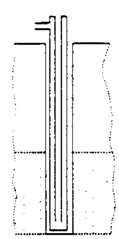
- Concept: steam delivery at 600 C
- Issue: Critical point = 374 C (non-isothermal heat delivery)



	Steam 600C 100Bar	Air 600C 100Bar	Salt 565C
Cp (kJ/kg-K)	2.44	1.13	1.54
V (m^3/kg)	0.040	0.027	0.00058
k (W/m-K)	0.093	0.064	0.55
μ (10^{-6}Pa-s)	3.47	4.02	114
Pr	0.91	0.71	3.2

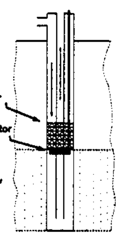
Steam delivery

- Concept:
  - Sensible heat delivery
  - Tube in tube
  - No packer
- Issues
  - Flux uniformity, pressure losses
  - Winter-outage freeze issues in distribution network
- Points to address
  - Calculate flux distribution, formation response, ΔP
  - Add distributed injection if needed for uniformity
- Operating below the critical point
  - Could deliver latent heat, isothermal conditions
  - Is heating at lower temperatures (rates) feasible?



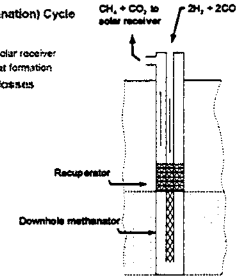
Combustion-gas issues, analysis

- Concepts:
  - Surface combustor
  - Downhole combustor
- Downhole advantages:
  - Recuperate downhole
  - Reduced insulated string requirements
  - Sandia direct experience
- Issues:
  - Emissions
  - Flux uniformity
  - Compressor requirements (no worse than steam)
  - Surface combustor: need to bring ~600C gas to surface & recuperate
  - Downhole – igniter and other downhole maintenance
- Points to address
  - Calculate flux uniformity, formation response, ΔP



Other Concepts

- Chemical Heat-Pipe (Reforming/Methanation) Cycle
  - $CH_4 + CO_2 \rightleftharpoons 2H_2 + 2CO$
    - Solar energy captured in syngas in solar receiver
    - Syngas methanated downhole to heat formation
  - Low distribution and overburden losses
  - Previous Sandia experience
  - Development needs
    - Scale up from lab size
    - Downhole methanator design
  - This is a long-term option!

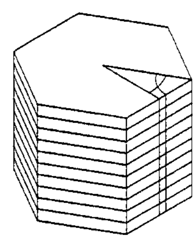


Thermal Models

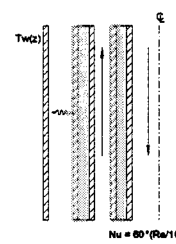
- Two efforts
  1. Simple models
     a. 1-D conduction in reservoir
     b. Correlation-based injection-string heat transfer
  2. Finite element model
- Progress in each effort

Simple thermal models

- 1-D conduction

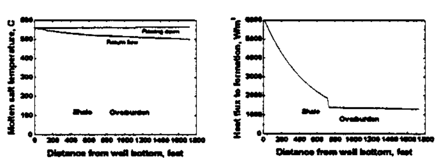


Correlations



Simple thermal models

- Example of results: 565 C molten salt, specified casing temperature (200 C overburden, 500 C shale)



Shale heating rate: 190 kW
Flow rate: 10^4 kg/hr

Overburden heating rate: 90 kW
ΔP: 215 psi

Finite Element Capabilities

- Code: COSMOS/M from SRAC
- 2-D/3-D
- Steady-state or transient
- Constant heat-input or pulse input
- Constant or temperature-dependent material properties
- Radiation

Finite Element Capabilities (cont'd)

- Can vary earth properties at various depths
- Can simulate phase change with step change in heat capacity at a certain temperature
- Simple fluid element link available for conjugate heat-transfer (full fluid model not needed)

Finite Element Model Verifications

- Test case model parameters:
  - 2-D conduction
  - infinite field – smaller model due to symmetry
  - constant material properties
  - no well bore natural convection
  - constant flux input and pulse (square-wave) input cases run

Finite Element Model Verification

- Test Case #1: Shell patent -- Figure 7
  - –5-spot, 230 W/ft, 90 days

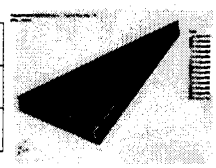
	Heater Temp (C)	Producer Temp (C)
Shell	500	300
Exact, 1x1	480	310
Exact, 7x7	814	606
FEA, infinite	794	585

  - –close - don't know Shell's assumptions such as conductivity, constant or varying, etc.

ite Element Model Verification (cont'd)

- Test Case #2: Shell patent Example 2
  - –7-spot, 10.55 MMBtu/day/well = 172 W/ft, 10 years

	Heater Temp (C)	Producer Temp (C)
Shell	750	300
FEA, infinite	635	337



  - –Producer well close, heater well not very close - don't know Shell's assumptions

Constant Input vs. Pulse Input

- Question: Solar vs Elec/Gas: Does it matter if flux is constant or a 3x flux level, but 1/3 time (same energy input)?
  - –Used same flux level , geometry as Shell patent Ex 2 (elec/gas)
  - –3x flux level for solar (assumption): 8 hrs on, 16 hrs off, square pulse

nstant Input vs. Pulse Input (cont'd)

- Could not run simulation to 10 years due to program limitation on number of data points on input power curve
- Ran out 3 years:

	Heater Temp (C)	Producer Temp (C)
Constant Flux	342	95
Pulse flux	478	92

nstant Input vs. Pulse Input (cont'd)

- Very similar temperatures at producer wells
- Solar pulse causes higher wall temps and fluctuations of about 150 °C
- If necessary, can possibly have software developer increase time curve limitations

Modeling Summary

- Analytical and FEA models match Shell patent values fairly well
- Finite element models will be generated as we progress with more complex issues (temperature-dependent properties, time varying BCs, non-linearities, etc.)
- Need to discuss level of detail that is required

Questions for Discussion

- Ranges of parameters
  - Overburden and shale thickness
  - Casing size
  - Well pattern and spacing
  - Heating rate
  - Reservoir properties
- Hardware
  - Shell process issues
  - Insulated tube data
  - Casing temperature issues
  - Well field startup sequence/timing
- Collaboration
  - Modeling (and level of detail needed)
  - Periodic reviews
- Feedback & Discussion

Methods & Sources for Subsurface Heating

Sixth- Month Meeting

September 11, 2002

Scott Jones
Scott Rawlinson
Jim Moreno

Meeting Agenda

12:00-12:15 Introductory remarks (Bob Ryan)
12:15-12:30 Secrecy agreements (Mark Allen)
12:30 - 1:45 Downhole combustor
- concepts (Jim Moreno)
- Sandia capabilities (Scott Rawlinson & jm)
- demo plan & cost (sr & Scott Jones)

1:45 - 2:00 Break
2:00 - 2:45 Status report
- heater models (sr & jm)
- heater hardware (jm)
- solar (sj)

2:45 - 3:30 Recap demo options (jm)
3:30 - 4:00 Discussion

Project Overview

- Consider 3 heat-delivery technologies
  - Molten salt
  - Steam
  - Downhole combustion
- Consider solar & non-solar heat sources
- Status
  - Models developed
  - Analysis progressing
- Expected results
  - Downhole recommendations
  - Heat source economics and environmental impacts

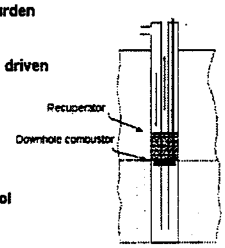
Downhole Combustors

Attractions:

- Can use on-site product
- Minimum heat loss to overburden
- Relatively easy to insulate
- No freeze-up issues
- Temperature rather than flux driven (inhomogeneity tolerant)

Challenges

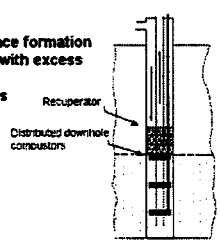
- Tight confines
- Materials temperatures
- Downhole ignition and control
- Compression costs



Downhole Combustor Concepts

Approach:

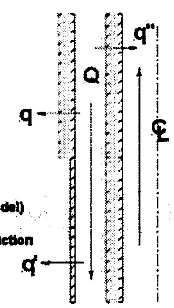
- Model the coupled heater and subsurface formation
- Limit flue gas & material temperatures with excess air (and/or water?)
- Consider single and distributed burners
- Nozzle or surface burners
- Determine optimum dimensions
- Determine recuperator requirements
- Consider natural gas first



Downhole Combustor Model

Well bore model:

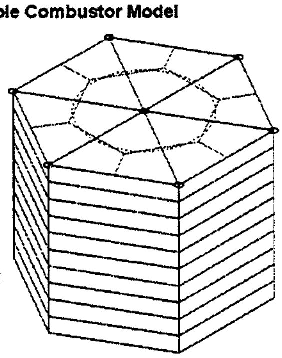
- Quasi steady
- Concentric insulated pipes
- Counter-flowing gases
- Compressible frictional flow
- Heat exchange between streams
- Heat loss to formation
- Heat addition at discreet points
- Specified combustion air T, P, and Mdot
- Specified casing temperature (from formation model)
- Casing flux provided to formation model
- Correlations used for film coefficients and wall friction
- ODE shooting technique solver



Downhole Combustor Model

Formation heat model:

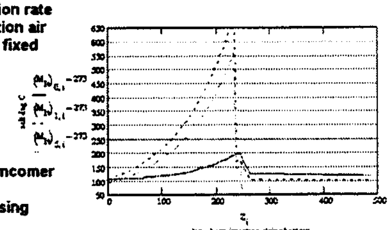
- Infinite triangular pattern
- Constant properties
- Conduction only
- Approximate the hexagonal symmetry element as a circle
- Divide depth into slabs with radial conduction only
- Zero flux at perimeter
- Flux boundary condition at injection well casing supplied by well-bore solver
- Radial differencing with variable Δr
- Implicit time differencing



Downhole Combustor Model Results

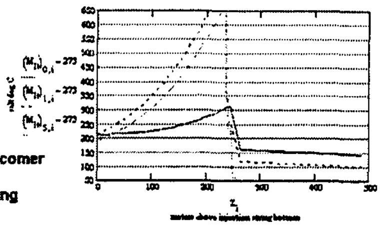
- 800' shale, 800' overburden
- 30' triangle pattern
- 200 kW combustion rate
- 100 atm combustion air
- 300% excess air, fixed
- At 200 hours.....

Traces:
Blue: downcomer
Red: riser
Green: casing



Downhole Combustor Model Results

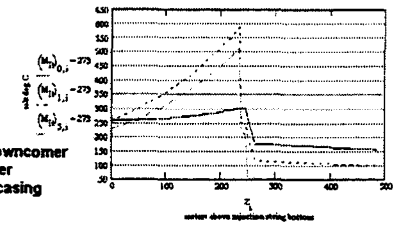
At 3000 hours:
•Rising preheat with fixed air flow causes high wall temperature



Traces:
Blue: downcomer
Red: riser
Green: casing

Downhole Combustor Model Results

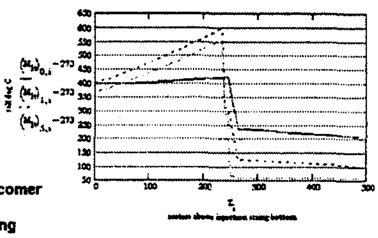
At 3000 hours:
•But now with air flow continually adjusted to give 600 C flue gas



Traces:
Blue: downcomer
Red: riser
Green: casing

Downhole Combustor Model Results

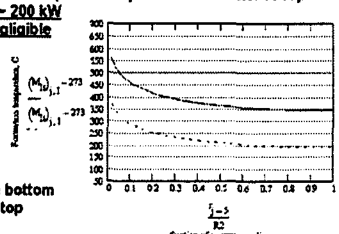
At 15000 hours...
•Note recuperator performance



Traces:
Blue: downcomer
Red: riser
Green: casing

Downhole Combustor Model Results

At 15000 hours:
•Energy balances within 1.8%
•Overburden loss = 2%
•*Thermal efficiency = 77% (can be improved with better recuperation)*
•Compressor size ~ 200 kW
•Friction losses negligible

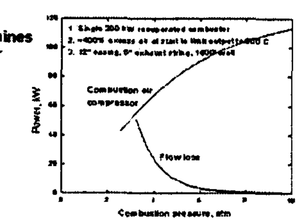


Traces:
Blue: shale bottom
Red: shale top

Downhole Combustor Model Results

Combustion air compression costs:

•Open loop
•Reducing pressure shrinks compressor, but still >50 kW
•Regeneration: more big machines
•Problem is large % excess air



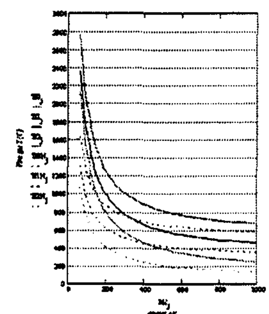
Downhole Combustor Model Results

Excess air requirements:

•200 kW heater
•3.6 gm/s natural gas
•No excess air:
66 gm/s air
2126 C flue gas (no preheat)
2768 C flue gas (500 C preheat)

•Excess air traces:
Red: 500 C preheat
Blue: 250 C preheat
Brown: no preheat

Dotted: 2 100-kW heaters



Downhole Combustor Concepts

Single vs multiple burners:

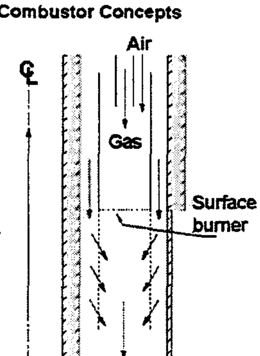
•Single burner:
No supply lines below burner
Supply lines only see high temperature at recuperator
Reduced electrical shorting concerns

•Multiple burners:
Reduced compression costs
More room per kW combustion rate

Downhole Combustor Concepts

Example:

•200 kW natural gas
•Metal matrix surface burner
•Acotech (Shell + Bekaert)
•AC 200 P1
•At 1 atmosphere:
•5 MW/m² max. firing intensity
•Blue flame mode
•6" ID x 11" OD = 0.04 m²
•Excess air to limit flue gas and material temperatures



Downhole Combustor Concepts

Summary:

- Downhole combustion model is running
- Distributed vs single burner tradeoffs underway
- Metal matrix burner is capable of required combustion intensity
- Vortex nozzle probably is, as well
- Insulation will be easier than with salt or steam
- Outstanding issues:
  - detailed burner design
  - ignition
  - fuel delivery
  - control

Sandia Downhole Combustor Capabilities

Direct experience

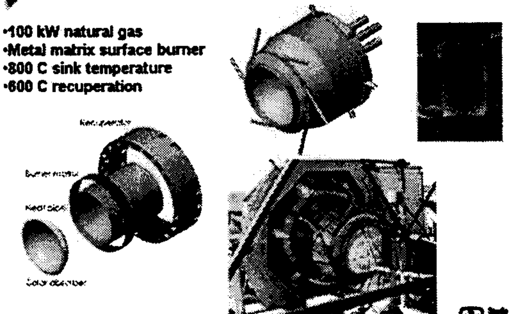
- 100 kW gas-fired hybrid solar receiver
- 1.2 MW downhole steam generator

Strengths

- Multi-program laboratory
- Broad range of capabilities
  - Design (would go to specialists for combustor)
  - Fabrication
  - Systems integration
  - Testing

Sandia hybrid receiver

- 100 kW natural gas
- Metal matrix surface burner
- 800 C sink temperature
- 600 C recuperation



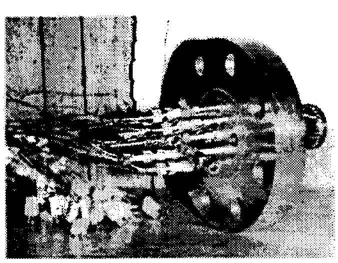
Sandia Downhole Steam Generator Development Program

- Propane
- Diesel
- Diesel/O_2
- Crude/O_2
- Nozzle burners

Sandia Downhole Steam Generator Development Program

Diesel/O_2

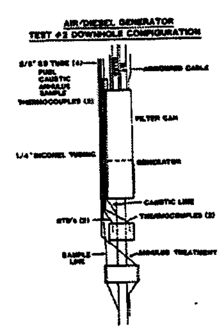
- Instrumented
- Glo-plug igniters
- 100-atm combustion
- Surface operation



Sandia Downhole Steam Generator Development Program

Diesel/air

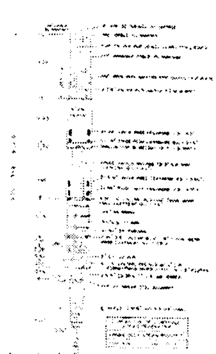
- Instrumented
- Glo-plug igniters
- 100-atm combustion
- Downhole operation



Sandia Downhole Steam Generator Development Program

Diesel/air

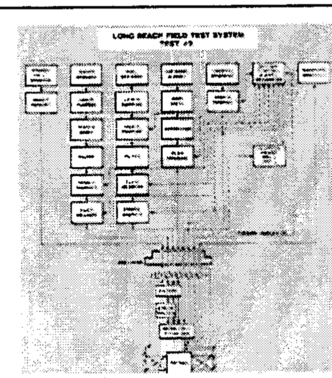
- Integrated with well hardware
- Showing dimensions



Sandia Downhole Steam Generator Development Program

Diesel/air

- Integrated with surface support equipment

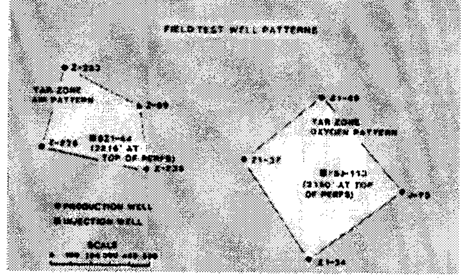


Sandia Downhole Steam Generator Development Program

Instrumentation and pump skids

Sandia Downhole Steam Generator Development Program

Long Beach Oil Development Company Tests



Sandia Downhole Steam Generator Development Program

TYPICAL AIR/DIESEL OPERATING CONDITIONS TEST #2 PHASE II

FUEL	3.3 lb/min
AIR	49 lb/min
WATER	84 lb/min
AIR/FUEL RATIO	14.8
FIRING RATE	4.0 MM Btu/hr.
QUALITY	40-50%
PRESSURE	1380 psi
TEMPERATURE	440°F

4 MM Btu/hr = 1.2 MW

Sandia Downhole Steam Generator Development Program

Problem areas

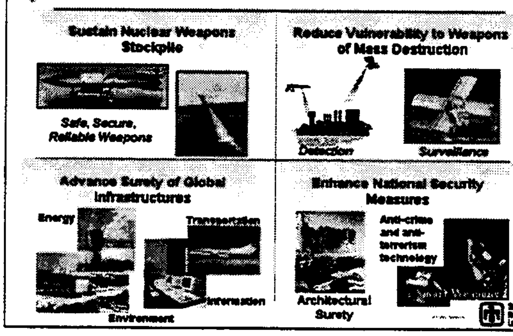
- Submerged compression-fitting leaks
- Glo-plug igniters (> few hundred hours)
- Downhole water filters
- Combustor liner alternating plasticity
- Compressor oil-mist detonation
- Funding

What worked

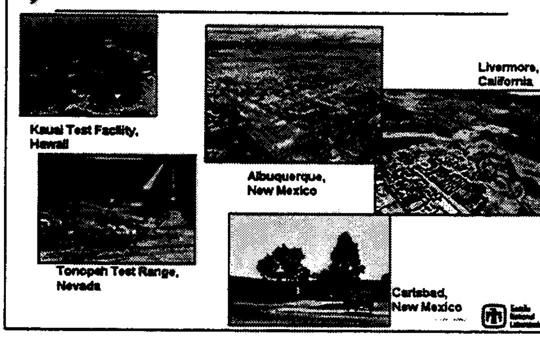
- Compression fittings with thick-wall tubing
- Sheathed thermocouples
- Tri-ethyl boron ignition
- Downhole water filters with O_2 scavenging
- Thin wall combustor liners (better)
- High-pressure combustion of diesel & crude

Sandia's Vision

Helping our nation secure a peaceful & free world through technology



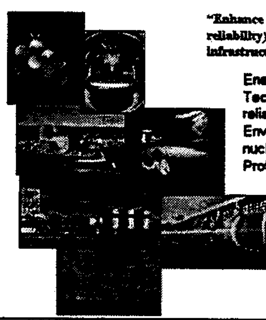
Sandia National Laboratories Today



Sandia — in round numbers

- **7,700 full-time employees**
  - ~6,800 in New Mexico
  - ~900 in California
- **600 buildings, 5M square feet**
- **1,450 Ph.D.'s, 2,100 Masters**
  - 54% engineering
  - 29% science and mathematics
  - 17% computing and other
- **Annual budget $1,700M**

Energy & Critical Infrastructures Strategic Business Unit (SBU)

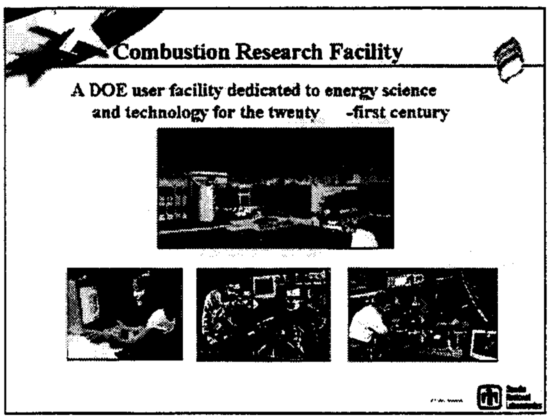


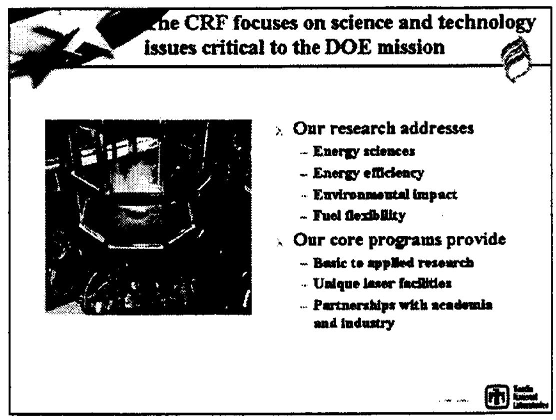
"Enhance the surety (safety, security, and reliability) of energy and other critical infrastructures"

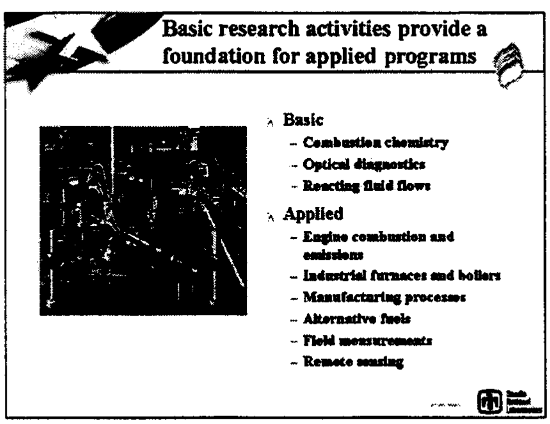
Energy research and earth sciences
Technology for clean, affordable, and reliable energy
Environmental stewardship and nuclear waste management
Protecting our U.S. Infrastructure

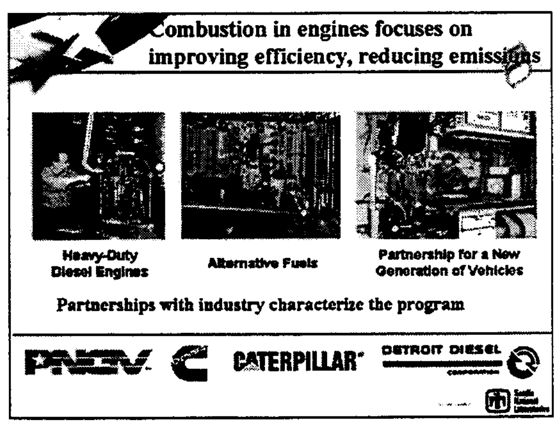

We develop technology for clean and affordable energy
Nuclear waste management
Environment
Energy research
Nuclear energy
Applied energy

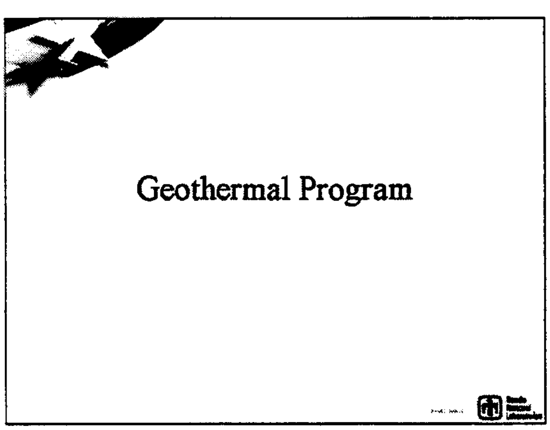

Partnerships Are Vital to Our Work
By FY 2005, we intend to bring in $130M in industry partnerships
We presently have 500 research projects with universities

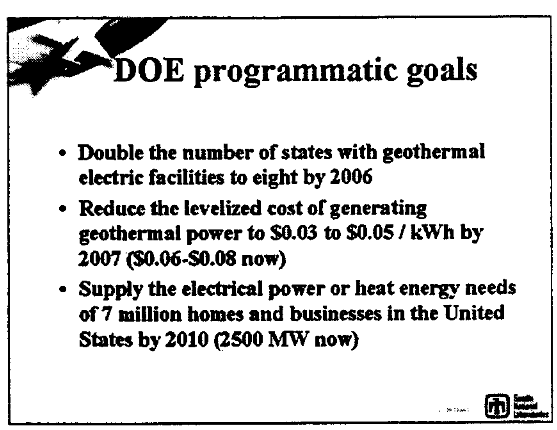

Combustion Research Facility
A DOE user facility dedicated to energy science and technology for the twenty -first century


The CRF focuses on science and technology issues critical to the DOE mission
Our research addresses
– Energy sciences
– Energy efficiency
– Environmental impact
– Fuel flexibility
Our core programs provide
– Basic to applied research
– Unique laser facilities
– Partnerships with academia and industry


Basic research activities provide a foundation for applied programs
Basic
– Combustion chemistry
– Optical diagnostics
– Reacting fluid flows
Applied
– Engine combustion and emissions
– Industrial furnaces and boilers
– Manufacturing processes
– Alternative fuels
– Field measurements
– Remote sensing

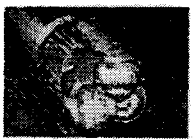

Combustion in engines focuses on improving efficiency, reducing emissions
Heavy-Duty Diesel Engines
Alternative Fuels
Partnership for a New Generation of Vehicles
Partnerships with industry characterize the program
CATERPILLAR
DETROIT DIESEL

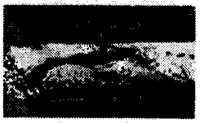

Geothermal Program


DOE programmatic goals
• Double the number of states with geothermal electric facilities to eight by 2006
• Reduce the levelized cost of generating geothermal power to $0.03 to $0.05 / kWh by 2007 ($0.06-$0.08 now)
• Supply the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010 (2500 MW now)

Geothermal Drilling is Very Difficult

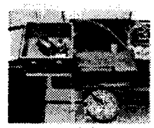
- Hard Rock
  - 240 MPa compressive strength
  - Abrasive, fractured
  - ROP < 6 m/hr, Bit life < 130 m
- Lost circulation
  - 15% of well cost
  - Large cracks (inches), difficult to plug
- High Temperatures
  - T > 300 °C (well temp)
- Corrosive Brines

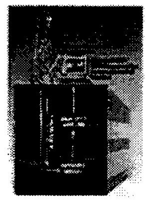




Program elements

- Hard-rock drill bits
- High-temperature electronics
- Lost circulation detection and mitigation
- Diagnostics-While-Drilling





Collaboration with Oil & Gas Industry benefits Geothermal research

- Oil and Gas Industry provides opportunities to field test our developments in an environment that is less harsh than geothermal.
  - First make it work...
  - Then make it work for geothermal
- The oil and gas industry provides market-pull for our technology.
  - It must become available in the market for it to be available for geothermal drilling.
  - Oil and gas helps reduce cost through economy of scale
- Many of the participants - Halliburton, Nabors, Epoch - are the same.

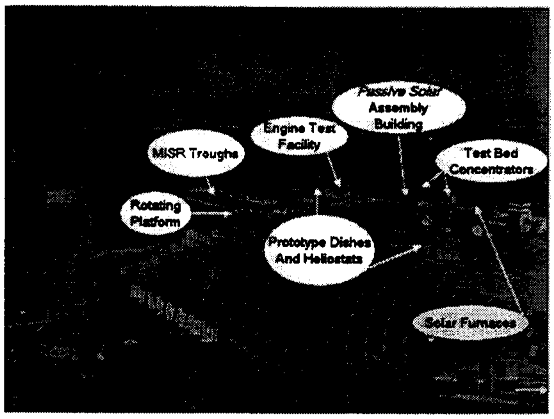
Sandia Geothermal Drilling Technology Program

Current Industry, University, and National Laboratory Participants -

Baker Hughes Inteq
Baker Oil Tools
Boart Longyear
Brookhaven National Laboratory
Caithness Energy
CalEnergy
California Energy Commission
Cooper Consultants
Cornell University
Drill Cool Systems
DOSECC
Dynaflow, Inc.
EDO Corporation
EGI Weathorford
Epoch Well Logging
Extreme Engineering
Geo Hills Associates
Geothermal Management Co.
Gulton Statham
Gas Research Institute
Halliburton Services
Hughes Christensen Co.
Livesay Consultants
Marconi, Inc.
Maurer Engineering
Maxwell Technologies
Nabors Drilling
NM Inst. of Mining and Tech.
Noble Drilling
Northstar Research
Novatek, Inc.
Oxbow Geothermal Corp.
Peek Measurements, Inc.
Petron
Pruett Industries
Security DBS
Smith International
Southern Methodist Univ.
SpecTran
Terra Tek
Technology Int'l
Thermochem, Inc.
Tonto Drilling
USGS
U. Oklahoma
U. Louisiana, Lafayette
Unocal Corporation

NSTTF Capabilities

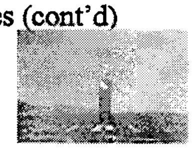
- Site Overview:



NSTTF Capabilities (cont'd)

Testing:

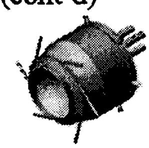
- Solar testing
- Sensible heat processes
- Engine testing
- Materials testing
- Simulation of aerodynamic heating and nuclear pulses

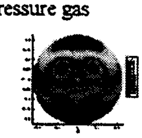


NSTTF Capabilities (cont'd)

Staff capabilities:

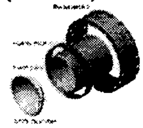
- Design, analysis, testing
- Welding – TIG, Arc, Flame; Steel, high-nickel alloys, aluminum
- Fabrication of structures, assemblies
- Vacuum, high pressure gas systems
- Electrical
- Electronics





NSTTF Capabilities (cont'd)

- Equipment:
  - Forklifts, cranes, aerial lifts
  - Vacuum systems
  - Heat rejection systems
  - Machine shop
  - High pressure bottles and fittings
  - Electronics laboratory
  - Heat lamps, electrical heaters
  - Gas-fired combustion equipment
  - Dynamometer
  - DAC systems
  - Need more? http://www.sandia.gov/Renewable_Energy/solarthermal/nsttf.html



Downhole Combustor Plan

- Concept: 200 kW-t burner at top of shale, or several distributed burners
- Recuperator at shale/overburden interface
- Phase I: Develop and test system at Sandia
- Phase II: Deploy system at Shell
- Design and development needed:
  - Burners
  - Recuperator
  - Insulated string

Downhole Combustor Plan (cont'd)

- Advantages:
  - Robust for heterogeneous formation
  - Minimal loss to overburden (50' recuperator adequate)
  - Continuous operation
  - Low cost
  - Does not required sealed insulation
- Disadvantages:
  - Burner development needed
  - High-temp igniters and cable need to be identified

Downhole Combustor Plan (cont'd)

- Costs and time frames:
  - Phase I: $1.2M, Year 1
  - Phase II: 0.4M, Year 2
- Details: next slide

Downhole Combustor Plan (cont'd)

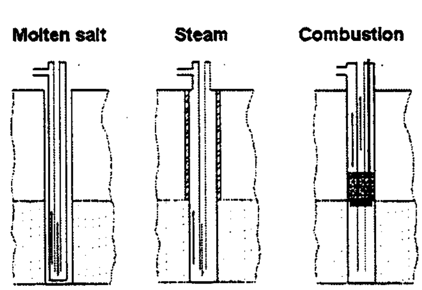
- Costs and time frames:

Activity	
[illegible]	[illegible]

Project Status Report

Primary Activities
- Develop heater concepts (salt, steam, DHC)
- Develop heater models
- Heater functional designs (materials, structural, cost)
- Heater parametric studies
- Solar concepts (salt, steam, chemical)
- Solar functional designs (layout, losses, cost, parametric studies)
- Field management
- Solar resources
- Solar benefits
- Recommendations
- Report

Heater Concepts



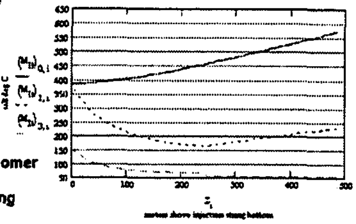
Correlation-Based Downhole Heater Models

Three models
- **Molten salt**
- **Steam**
- **Downhole combustion**
- **Similar logic for all three**

Results
- **DHC already covered**
- **Molten salt**
  - **Diurnal operation – freeze issues**
  - **Continuous operation – startup and pump issues**
  - **Shale heat extraction**
- **Steam**
  - **Continuous operation – pressure loss issues**

Molten Salt Model Results

- 800' shale, 800' overburden
- 30' triangle pattern
- 300 kW heater rate
- At 1 hour.....

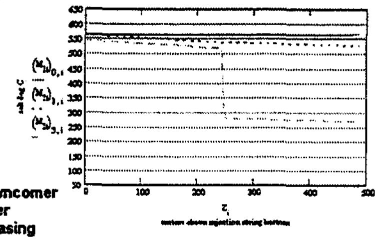


Traces:
Red: downcomer
Blue: riser
Green: casing

- Solar salt freezes at 220 C, HiTech at 140C

Molten Salt Model Results

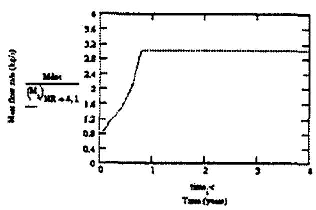
At 26 months.....



Traces:
Red: downcomer
Blue: riser
Green: casing

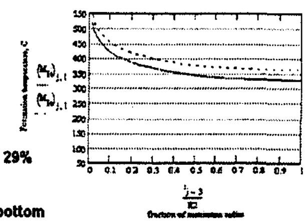
Molten Salt Model Results

- Flow rate is increased to maintain 300 kW input, but only up to 3 kg/sec
- P_{pump} = 4.4 hp



Molten Salt Model Results

At 26 months.....

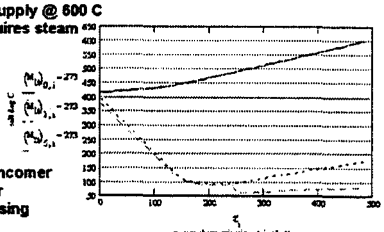


- Overburden loss = 29%

Traces:
Red: shale bottom
Blue: shale top

Steam Model Results

- 800' shale, 800' overburden
- 30' triangle pattern
- 300 kW heater
- 100 atm steam supply @ 600 C
- Closed loop requires steam compressor
- At 100 hours.....

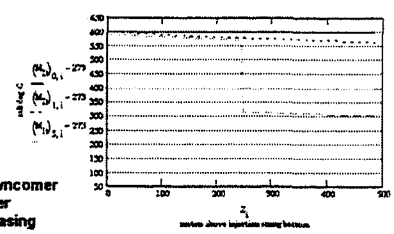


Traces:
Red: downcomer
Blue: riser
Green: casing

- Need to pump condensate?

Steam Model Results

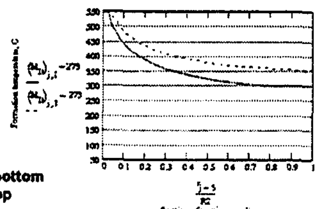
- At 15000 hours.....



Traces:
Red: downcomer
Blue: riser
Green: casing

Steam Model Results

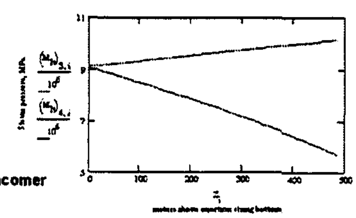
- At 15000 hours.....



Traces:
Blue: shale bottom
Red: shale top

Steam Model Results

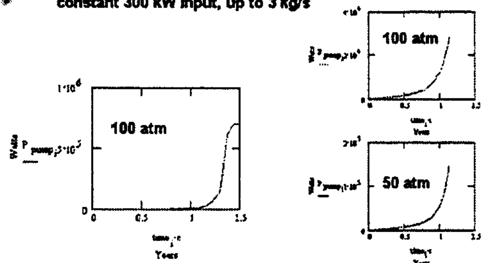
- At 15000 hours.....



Traces:
Red: downcomer
Blue: riser

Steam Model Results

- Steam mass flow rate is increased as necessary for a constant 300 kW input, up to 3 kg/s



- 100 atm vs 50 atm shows that lower pressure is worse
- Compression costs suggest lower flow rate or condensing steam in second well

Finite Element Models

- Code used: COSMOS/M from SRAC
- Several models developed:
  - –3-D, with fluid flow
  - –3-D, no fluid flow
  - –2-D, no fluid flow
  - –2-D, with fluid flow
- All models used the following:
  - –Radiation heat xfer to formation
  - –Constant material properties

Finite Element Models (cont'd)

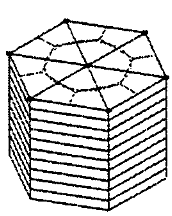
- Due to huge aspect ratio, have too many elements to run on PC:
  - –Performed coordinate transformation in vertical direction
  - –If z' = z/N, then
    - $k' = k/N^2$
    - $c_p' = c_p/N$
  - –Results in a workable size problem

Finite Element Models (cont'd)

- 3-D models with fluid flow:
  - –Much too computational-intensive
  - –Would need months to run on PC
  - –Sandia computational group:
    - Sandia codes would not be much faster
    - Confirmed complications (radiation, anisotropic properties, transient BCs)

Finite Element Models (cont'd)

- 3-D models with fluid flow (cont'd):
  - –Decided 2-D adequate for now:
    - Much faster for screening
    - Axisymmetric good assumption for triangular pattern:
      - –Planes of symmetry result in a narrow slice
      - –Hexagon pattern doesn't look much different than an inscribed circle



Finite Element Models (cont'd)

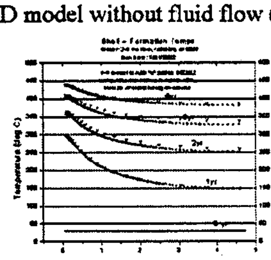
- 3-D models without fluid flow:
  - –Constant temperature radiation to casing
  - –Basis: In late time, salt in 550C, out at 500C, radiation at 525C is a reasonable assumption
  - –Poor assumption for early time, good for later time
  - –Can verify long-term temperature profiles are similar, if needed, at later date (still computer-intensive)

Finite Element Models (cont'd)

- 2-D model without fluid flow:
  - –Same constant temperature radiation to casing, same arguments as 3-D without fluid flow
  - –SRAC made a FEA version with enough data points to run out a 4-year run
  - –Runs fairly quickly

Finite Element Models (cont'd)

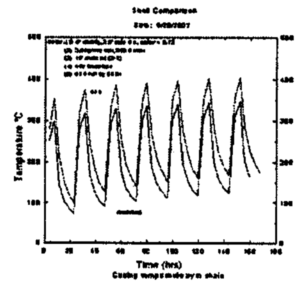
- 2-D model without fluid flow (cont'd):



Finite Element Models (cont'd)

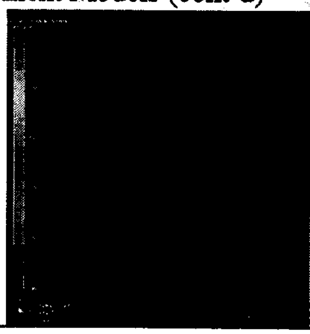
- 2-D model with fluid flow:
  - –Full conjugate heat-transfer model
  - –Run times much longer
  - –Many troubles with software support for flow module
  - –Short run comparison to Moreno ....
  - –Hope to have new flow code soon (present version does not support radiation

Finite Element Models (cont'd)



Finite Element Models (cont'd)

- 2-D model with fluid flow (cont'd):



Modeling Summary

- Analytical vs FEA models
  - Models match fairly well
  - Use analytical models for parametric cases (faster to change geometry, etc)
  - Use FEA models for:
    - Analytical model verification
    - Calculate losses to overburden
    - If 3-D temperature distributions are needed

Downhole Heater Hardware

Downhole Combustor
- Already covered

Molten Salt
- Injection string
- Well head

Steam
- Injection string
- Well head

Injection String

Requirements

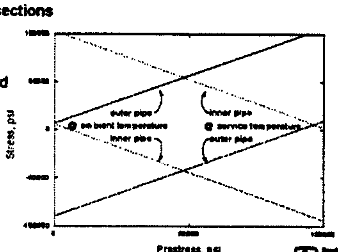
- Compatible with nitrate-salt (Austenitic or >9Cr-Mo steel) or steam
- For molten salt, all welded (no threaded joints)
- Insulation must be isolated from steam or salt
- Insulation should be equivalent to 0.015 Btu/hr-ft-R (0.026 W/m-K)
- Adequate yield & creep strength for pressure & string weight
- Tolerant of differential thermal expansion

Molten-Salt Injection String

Vacuum-insulated string, weld seal joints (0.026 W/m-K)

Assumptions:
- Equal wall cross sections
- 565 C inner
- 220 C outer

Stainless steel yield
- 32 kpsi @ 20 C
- 15 kpsi @ 565 C



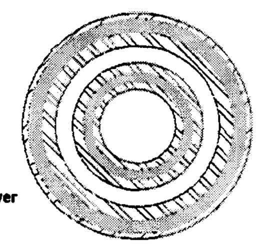
Molten-Salt Injection String

Insulated pipeline technology: InTerPipe/Izoflex

Izoflex: 0.02 W/m-K @ 565 C
Not hermetic

Inner insulated string:
- Spooled or field orbital weld
- Not hermetic

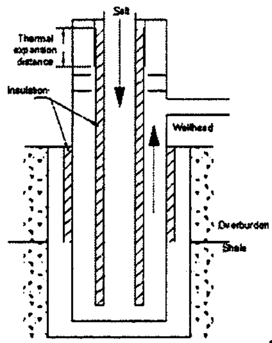
Outer string:
- Spooled
- Field-applied outer insulation
- Non-continuous protective cover



Molten-Salt Well Head

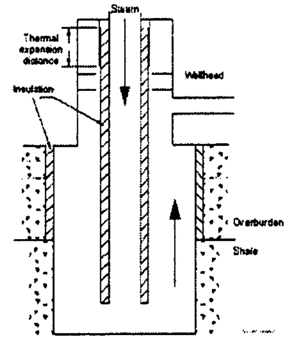
•Gravity isolation of salt from insulation

•Fixed high-pressure connection point



Molten-Salt Injection String/Well head

•Isolation of steam from insulation requires water-cooled seal/purging



Insulated String Issues

•Frictional forces during expansion
•Buckling
•Actual thermal performance

•Should be resolved by sub-scale tests

Downhole-Heater Issues Summary

- •Molten Salt
  - •Insulated string
  - •Early-time freezing
  - •Overburden loss
- •Steam
  - •Insulated string
  - •High pressure
  - •Early-time condensation
  - •Overburden loss
- •Downhole Combustor
  - •Burner design
  - •Ignition
  - •Control
  - •High pressure or multiple burners

Combined Well Concept

- If Shell desires to heat injector + producer wells
- Salt downhole sounds promising
  - Combined injector + extraction well
  - "Losses" to overburden heat extraction well
  - Product produced much faster (improves economics)
  - Not necessarily a solar concept
    - Could heat salt with gas burner using on-site products
    - Option for solar-only or hybrid solar/gas
    - Potential environmental incentives/benefits

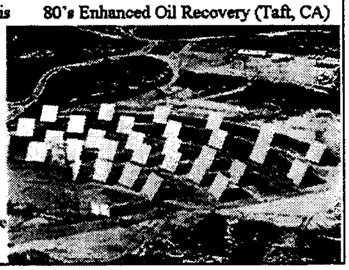
Solar Tasks

- Solar system conceptual designs
- Solar systems functional designs (layout, losses, cost, parametric studies)
- Field management
- Solar resources
- Solar benefits

Solar system conceptual designs

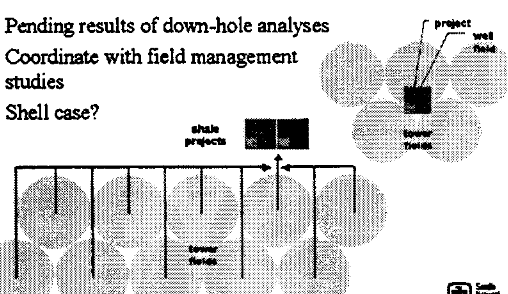
- Demo plant cost estimates for Salt Systems
  - DELSOL field layouts
  - Rough cost analysis
  - Use Solar Two surplus parts
  - Billboard receiver
  - Hybrid option
- To do
  - Large plants (hybrid?)
  - Solar steam
  - Chemical heat pipe

80's Enhanced Oil Recovery (Taft, CA)



Solar Systems Functional Designs, Field Management

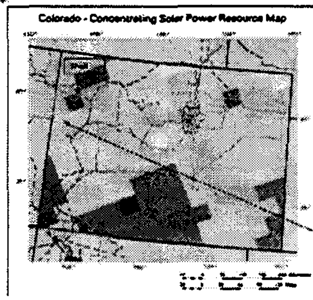
- Pending results of down-hole analyses
- Coordinate with field management studies
- Shell case?



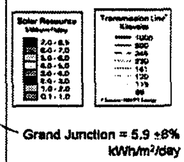
Solar Analysis Efforts

- If we refocus on downhole combustor, it would require reduction in labor elsewhere
  - Limit solar systems analysis
  - Ignore off-design temperatures in receiver
  - Shell suggestions for re-allocating resources?

Solar Resources

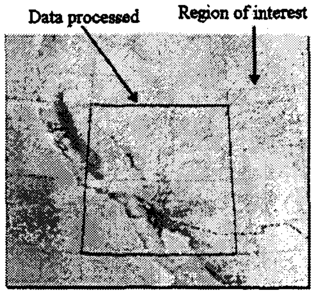


- Use best available data for analysis

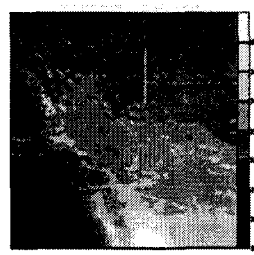


Solar resources

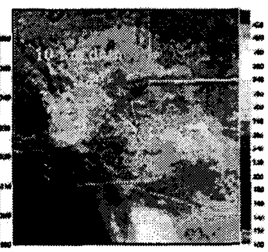
Satellite-Derived Techniques Provide Improved Site-Time Coverage (NREL + SUNY/Albany)



Solar Resources



GLOBAL IRRADIANCE (average W/sq.m)



DIRECT IRRADIANCE (average W/sq m)

Solar Benefits Study

- Still to do
- Environmental benefits
  - Carbon emission reduction
  - Other pollutants (NO_x, SO_x, Hg, etc.)
  - Fuels evaluated
    - Natural gas
    - Shale oil – Shell data?
- Tax benefits
- Public acceptance/approval

Tax Incentives for Solar

- Valuable tax credits for solar power
- Apply to solar powered oil shale extraction ????
- Accelerated, 5-year depreciation
  - Economic Recovery Tax Act of 1981 (ERTA) (P.L. 97-340)
- 10% Investment Tax Credit
  - Energy Tax Act of 1978 (ETA) (P.L. 95-618)
  - Energy Policy Act of 1992 (EPAct) (P.L. 102-486)

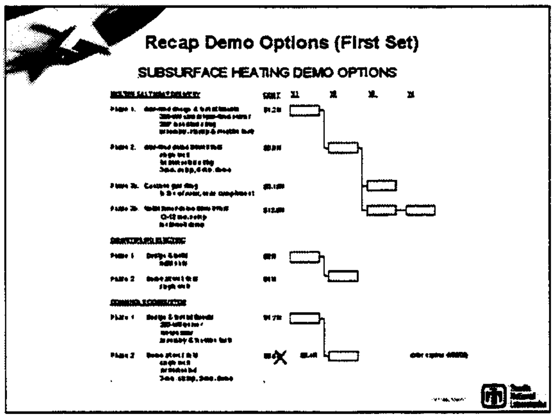
Example of Tax Incentives

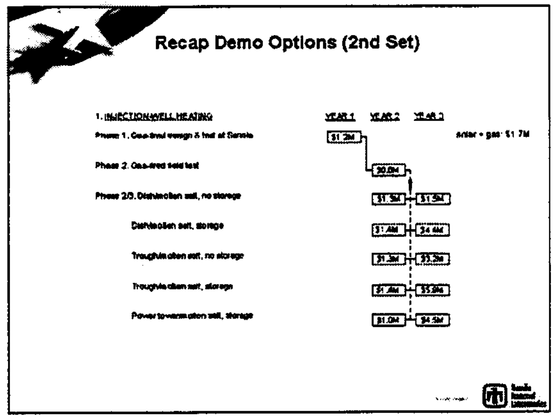
- 100 MWe, 73% capacity factor power tower
- $311M construction cost
- If 50/50 debt/equity, get ½ back in first year
- Levelized Electricity Cost (2001$/kWh) = 0.046

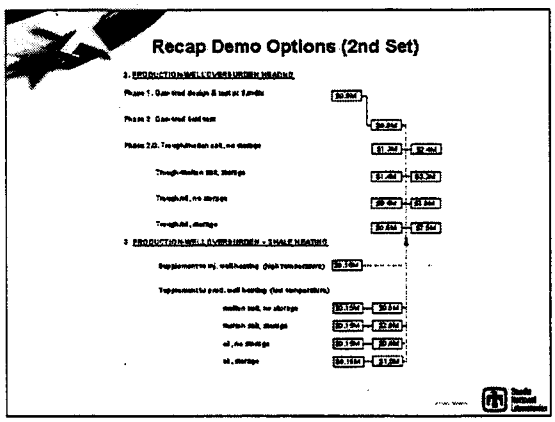
Millions of 2002$ Year	Adjusted Income	Qualified Deprctn A	(Non-cash) Taxable Income	Income Tax Before Credits	Investment Based ITC	Net Income Tax	Debt Principal	Operating Income	Distributed Cash (After tax)
1	7.21	111.62	-104.41	39.63	33.57	73.20	-4.86	2.35	-75.52
2	7.94	82.82	-74.98	28.48	0.00	28.44	-5.24	2.70	-31.18
3	8.69	49.75	-41.06	15.58	0.00	15.59	-5.60	3.09	-18.67
4	9.48	35.11	-25.63	9.73	0.00	9.73	-6.00	3.49	-13.22
5	10.31	35.11	-24.81	9.42	0.00	9.42	-6.42	3.89	-13.31
6	11.17	4.40	6.77	-2.57	0.00	-2.57	-6.86	4.30	-1.73
year 7-20									-0.410 [illegible]
year 21-30									-19.20 -7[illegible]

Demo Options

- Phase one (downhole hardware at Sandia)
  - Design
  - Develop
  - Test
- Phase two (surface & downhole at Shell)
  - Install
  - Test


Recap Demo Options (First Set)
SUBSURFACE HEATING DEMO OPTIONS


Recap Demo Options (2nd Set)


Recap Demo Options (2nd Set)

APPENDIX D: CRADA PROJECT PLAN

Mission: Provide analysis to Shell E&P per CRADA Statement of Work

Goal: Produce reports analyzing heat delivery systems for an array of shale oil wells and summarizing the potential for using solar energy systems, by 10/30/2002.

Objectives:

1. Select heat delivery systems
2. Design downhole heaters
3. Design surface heat source
4. Address well field management issues (see issue regarding analysis complexity in Restrictions section)
5. Define solar resource at Shell site
6. Assess environmental benefits of using solar energy
7. Develop basic plan for next step
8. Evaluate and report findings

Scope:

- Include electric heater (performance only), molten nitrate salt, steam, downhole combustor, chemical heat pipe
- Design at functional level (not detailed design)
- Address corrosion considerations only inside well casing
- Nominal well geometry is: 0.5 x 0.5 mile well field and 1.25 x 1.25 mile project at 1.1 GWt, triangular pattern with 30 ft injector well spacing, 18 injectors/producer, 800 ft of overburden, 800 ft of shale, 26 gallons oil/ton of shale (Fisher Assay), 250 W/ft heating rate, 6 in. hole
- Range of well geometry parameters: 20-40 foot injector well spacing (triangular pattern), 400-1000 ft of overburden, 300-850 ft of shale interval, 6-12 in. well diameter, 12 to 24 injectors/producer
- Environmental benefit evaluation will consider air emissions, water usage, and land area for the following options: coal and well-gas electricity (Rankine, Brayton, or Combined Cycle for well-gas), well-gas direct firing.

Restrictions, Assumptions, Constraints

- Assume underground formation has constant heat transfer properties (neglect chemistry and variable properties, treating just a conduction problem.
- Assume internal well bore heat transfer by natural convection is negligible
- Regarding startup: the design and analysis of the complete system, including both downhole and surface, is very complex. Consequently, we want to eliminate as many concepts as possible before startup analysis is performed. We expect that startup analysis will require simplifying assumptions. A comprehensive treatment would require resources beyond the scope of this initial effort.
- Regarding shutdown: qualitatively assess which technologies might be suitable for recovering heat from a converted pattern, to be used to preheat another.

Activities (by Objective)

1. Select heat delivery systems
   - Identify systems
   - Look for show stoppers (e.g. excessive system pump power)
   - Down select
2. Design downhole heaters
   - Develop conceptual designs (configurations, operating strategies including startup and diurnal heating) for nominal conditions
   - Analyze thermal performance and parasitic energy use
   - Develop functional design for nominal conditions (select materials, perform structural analysis, assess cost)
   - Conduct parametric study for well geometry using defined ranges as listed in scope and assumptions above
3. Design surface heat source
   - Develop conceptual design (configuration including dish/tower, location versus well field, assuming standard solar power inlet/outlet temperatures) for nominal well field conditions
   - Analyze optical and thermal performance
   - Analyze surface parasitic energy use
   - Develop functional design for nominal shale conditions (well/solar field layout and management, assess cost)
   - Parametric study around well energy requirements
4. Address well field management issues (see issue regarding analysis complexity in Restrictions section above)
   - Interface downhole and surface analyses (advanced design tools would eventually be required for a comprehensive analysis; simplifying assumptions would be used here)
   - Analyze operating strategies including startup, inlet/outlet temperatures
   - Conduct parametric study for well geometry using defined ranges as listed in scope and assumptions above
5. Define solar resource at Shell site
6. Assess environmental benefits of using solar energy (see Assumptions section above)
7. Develop basic plan for next step
   - Recommendations for demonstration project
   - Estimate resources for demonstration project
   - Recommendations for full-scale project
8. Evaluate and report findings
   - Draft
   - Shell review
   - Final

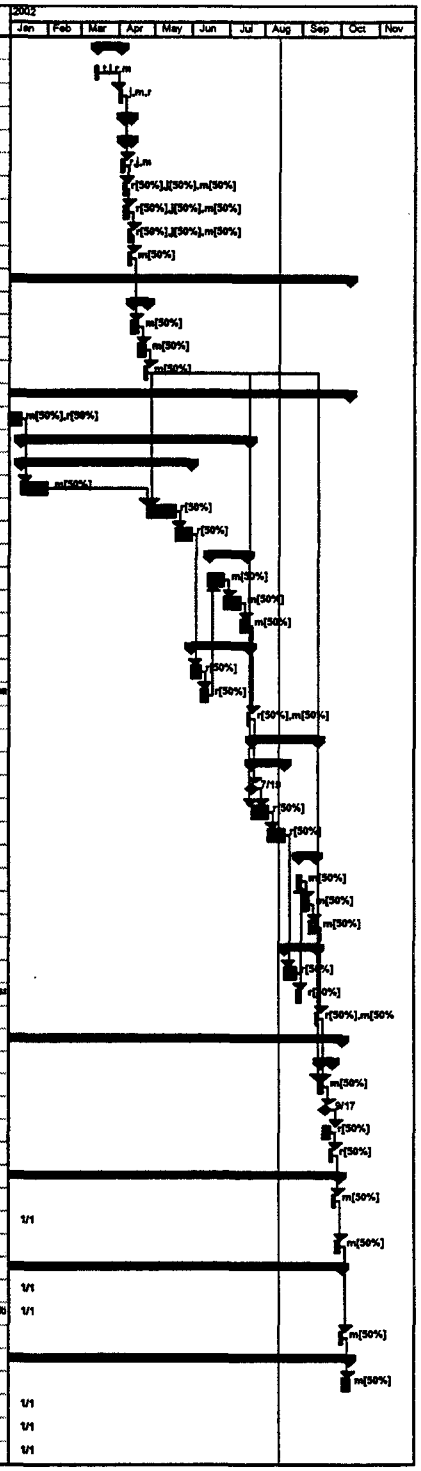
CRADA TASKS AND ESTIMATED WORK DAYS ("2nd" is final plan estimate)

		Work day estimates	
		1st	2nd
1.	**0. Project kickoff and planning**	**10**	**10**
2.	Kickoff meeting at Shell	4	4
3.	Project planning	6	6
4.	**1. SELECT HEAT DELIVERY SYSTEMS**	**7**	**7**
5.	**Identify systems**	**7**	**7**
6.	Brainstorm heat delivery options	1.5	1.5
7.	Identify possible show stoppers	2	2
8.	Analyze problems	2	2
9.	Down select to promising concepts	0.5	0.5
10.	Document options	1	1
11.	**2. DESIGN DOWNHOLE HEATERS**	**160**	**83**
12.	**Develop conceptual downhole designs for nominal conditions**	**5**	**5**
13.	Develop conceptual drawings	2	2
14.	Develop operating strategies for each concept	2	2
15.	Consider diurnal heating issues	1	1
16.	**Analyze thermal performance and parasitic energy use for each concept**	**155**	**78**
17.	First cut at analytic and numeric models for electric heater		7
18.	**Analyze downhole molten salt**	**69**	**40**
19.	**Develop molten salt downhole models**	**40**	**21**
20.	Develop analytical models for molten salt downhole	15	8
21.	Develop numerical models for molten salt downhole	15	8
22.	Debug molten salt models	10	5
23.	**Develop molten salt functional design for nominal conditions**	**20**	**12**
24.	Select molten salt system materials	5	5
25.	Perform molten salt structural analysis	10	5
26.	Assess molten salt system costs	5	2
27.	**Conduct parametric study of molten salt for well geometry changes**	**9**	**7**
28.	Run ~9 parametric cases for molten salt	5	3
29.	Compile molten salt parametric study results (temperature vs. time+position, thermal losses, pumping power)	2	2
30.	Document molten salt results and issues	2	2
31.	**Analyze downhole steam**	**38**	**23**
32.	**Develop steam downhole models**	**20**	**10**
33.	Modify analytical models for steam concept	5	0
34.	Modify numerical models for steam concept	5	5
35.	Debug steam models	10	5
36.	**Develop steam functional design for nominal conditions**	**9**	**6**
37.	Select steam materials	2	2
38.	Perform steam structural analysis	5	2
39.	Assess steam costs	2	2
40.	**Conduct parametric study of steam for well geometry changes**	**9**	**7**
41.	Run ~9 parametric cases for steam	5	3
42.	Compile steam parametric study results (temperature vs. time+position, thermal losses, pumping power)	2	2
43.	Document steam results and issues	2	2
44.	**Analyze downhole combustor**	**38**	**7**
45.	**Develop downhole combustor models**	**20**	**4**
46.	Analyze recuperator performance, geometry	5	1
47.	Modify analytical models for down hole combustor concept	5	0
48.	Modify numerical models for down hole combustor concept	5	2
49.	Debug combustor models	5	1
50.	**Develop downhole combustor functional design for nominal conditions**	**9**	**2**
51.	Select down hole combustor materials	2	1
52.	Perform down hole combustor structural analysis	5	0
53.	Assess down hole combustor costs	2	1
54.	**Conduct parametric study of down hole combustor for well geometry changes**	**9**	**1**
55.	Run ~9 parametric cases for down hole combustor	5	0
56.	Compile down hole combustor parametric study results (temperature vs. time+position, thermal losses, pumping power)	2	0
57.	Document down hole combustor results and issues	2	1
58.	**Analyze downhole chemical heat pipe**	**10**	**1**
59.	Research reaction chemistry	2	1

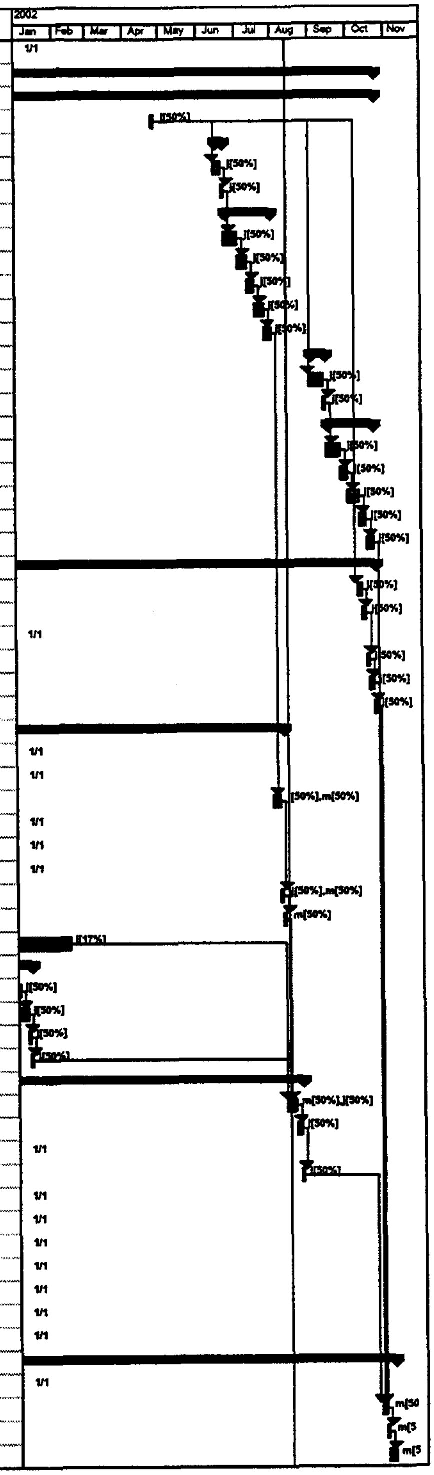
60.	Explore catalyst preheat issues	2	0
61.	Modify analytical models for chemical heat pipe concept	2	0
62.	debug chemical heat model	2	0
63.	Document chemical heat pipe results and issues	2	0
64.	**3. DESIGN SURFACE HEAT SOURCE ASSUMING SOLAR ELECTRIC OPERATING TEMP.**	**60**	**42**
65.	**Develop solar system conceptual designs**	**60**	**42**
66.	Define 3 values of well power for parametric study	1	1
67.	**Develop conceptual solar system for molten salt down hole concept**	**3**	**3**
68.	Design/analyze concptual solar system for molten salt downhole	2	2
69.	Document molten salt conceptual design results and issues	1	1
70.	**Develop molten salt functional design for nominal well power requirement**	**23**	**13**
71.	Develop solar/well-field layout and preliminary piping of molten salt solar system	10	4
72.	Analyze molten salt thermal and parasitic piping losses	5	3
73.	Assess cost of molten salt solar system	3	2
74.	Run 3 cases of well power parametric study	3	2
75.	Document solar system results for molten salt downhole	2	2
76.	**Develop conceptual solar system for steam down hole concept**	**5**	**5**
77.	Design/analyze conceptual solar system for steam downhole	4	4
78.	Document steam conceptual design results and issues	1	1
79.	**Develop steam functional design for nominal well power requirement**	**13**	**13**
80.	Develop solar/well-field layout and preliminary piping of steam solar system	4	4
81.	Analyze thermal and parasitic piping losses	2	2
82.	Assess cost of steam solar system	3	3
83.	Run 3 cases of well power parametric study	2	2
84.	Document solar system results for steam downhole	2	2
85.	**Develop conceptual solar system for chemical heat pipe down hole concept**	**15**	**7**
86.	Design solar system for chemical heat pipe concept	5	2
87.	Analyze performance, storage of chemical heat pipe	3	1
88.	Document chemical heat pipe conceptual design results and issues	1	0
89.	Analyze thermal and parasitic piping losses	2	1
90.	Assess cost of chemical heat pipe solar system	2	1
91.	Document solar system results for chemical heat pipe concept	2	2
92.	**4. ADDRESS WELL FIELD MANAGEMENT ISSUES (INITIAL LOOK)**	**35**	**8**
93.	Shell picks one case for analysis by Sandia	1	0
94.	Develop finite element model for well heat extraction	3	0
95.	Analyze freeze issues for startup and shutdown (if molten salt selected by Shell)	5	5
96.	Develop simplified well model, e.g. To=f(Ti, flow rate, Twell)	10	0
97.	Connect simple well model into a well field model	5	0
98.	Analyze solar system performance/cost for variable temperature operation	3	0
99.	Analyze startup and shutdown strategies	5	2
100.	Document results of well field management (incl. suggestions for future analysis)	3	1
101.	**5. COLLECT SOLAR RESOURCE AND GEOGRAPHICAL DATA FOR SHELL SITES**	**5**	**5**
102.	**6. ASSESS ENVIRONMENTAL BENEFITS OF USING SOLAR ENERGY (AIR, WATER, LAND)**	7	4.5
103.	Shell defines baseline non-solar system(s) for comparison	1	0.5
104.	Analyze baseline system(s) impacts	2	2
105.	Analyze solar impact using 1 Shell case from objective 4	2	1
106.	Document comparative environmental benefits	2	1
107.	**7. DEVELOP RECOMMENDATIONS FOR NEXT STEP**	**22**	**7**
108.	Evalute prior analysis to identify promising options	5	5
109.	Recommend concepts worth pursuing & sources of industrial support	1	1
110.	Develop scoping-level description of a full-scale project	3	0
111.	Identify areas needing further investigation/experimentation	1	1
112.	**Develop recommendations for a small demonstration project**	12	0
113.	Develop down hole demo options	2	0
114.	Develop solar system demo options	2	0
115.	Estimate cost and performance of demo concepts	3	0
116.	Identify issues/tradeoffs among options	1	0
117.	Estimate resources for small demonstration project	2	0
118.	Document small demo options and Sandia participation	2	0
119.	**8. EVALUATE AND REPORT FINDINGS**	**19**	**10**
120.	Progress meeting with Shell	4	0
121.	Draft report	10	5
122.	Shell reviews report	1	1
123.	Final	4	4
	TOTAL WORK DAYS	**325**	**176.5**

CRADA GANTT CHART SCHEDULE

ID	Task Name
1	**0. Project kickoff and planning**
2	Kickoff meeting at Shell
3	Project planning
4	**1. Select heat delivery systems**
5	**Identify systems**
6	Brainstorm heat delivery options
7	Identify possible show stoppers
8	Analyze problems
9	Down select to promising concepts
10	Document options
11	**2. Design downhole heaters**
12	**Develop conceptual downhole designs for nominal conditions**
13	Develop conceptual drawings
14	Develop operating strategies for each concept
15	Consider diurnal heating issues
16	**Analyze thermal performance and parasitic energy use for each concept**
17	First cut at analytic and numeric models for electric heater
18	**Analyze downhole molten salt**
19	**Develop molten salt downhole models**
20	Develop analytical models for molten salt downhole
21	Develop numerical models for molten salt downhole
22	Debug molten salt models
23	**Develop molten salt functional design for nominal conditions**
24	Select molten salt system materials
25	Perform molten salt structural analysis
26	Assess molten salt system costs
27	**Conduct parametric study of molten salt for well geometry changes**
28	Run ~9 parametric cases for molten salt
29	Compile molten salt parametric study results (temperature vs. time+position, therma
30	Document molten salt results and issues
31	**Analyze downhole steam**
32	**Develop steam downhole models**
33	Modify analytical models for steam concept
34	Modify numerical models for steam concept
35	Debug steam models
36	**Develop steam functional design for nominal conditions**
37	Select steam materials
38	Perform steam structural analysis
39	Assess steam costs
40	**Conduct parametric study of steam for well geometry changes**
41	Run ~9 parametric cases for steam
42	Compile steam parametric study results (temperature vs. time+position, thermal los
43	Document steam results and issues
44	**Analyze downhole combustor**
45	**Develop downhole combustor models**
46	Analyze recuperator performance, geometry
47	Modify analytical models for down hole combustor concept
48	Modify numerical models for down hole combustor concept
49	Debug combustor models
50	**Develop downhole combustor functional design for nominal conditions**
51	Select down hole combustor materials
52	Perform down hole combustor structural analysis
53	Assess down hole combustor costs
54	**Conduct parametric study of down hole combustor for well geometry changes**
55	Run ~9 parametric cases for down hole combustor
56	Compile down hole combustor parametric study results (temperature vs. time+positi
57	Document down hole combustor results and issues
58	**Analyze downhole chemical heat pipe**
59	Research reaction chemistry
60	Explore catalyst preheat issues
61	Modify analytical models for chemical heat pipe concept
62	debug chemical heat model



ID	Task Name
63	Document chemical heat pipe results and issues
64	**3. Design surface heat source assuming solar electric operating temperatures**
65	**Develop solar system conceptual designs**
66	Define 3 values of well power for parametric study
67	**Develop conceptual solar system for molten salt down hole concept**
68	Design/analyze concptual solar system for molten salt downhole
69	Document molten salt conceptual design results and issues
70	**Develop molten salt functional design for nominal well power requirement**
71	Develop solar/well-field layout and preliminary piping of molten salt solar system
72	Analyze molten salt thermal and parasitic piping losses
73	Assess cost of molten salt solar system
74	Run 3 cases of well power parametric study
75	Document solar system results for molten salt downhole
76	**Develop conceptual solar system for steam down hole concept**
77	Design/analyze conceptual solar system for steam downhole
78	Document steam conceptual design results and issues
79	**Develop steam functional design for nominal well power requirement**
80	Develop solar/well-field layout and preliminary piping of steam solar system
81	Analyze thermal and parasitic piping losses
82	Assess cost of steam solar system
83	Run 3 cases of well power parametric study
84	Document solar system results for steam downhole
85	**Develop conceptual solar system for chemical heat pipe down hole concept**
86	Design solar system for chemical heat pipe concept
87	Analyze performance, storage of chemical heat pipe
88	Document chemical heat pipe conceptual design results and issues
89	Analyze thermal and parasitic piping losses
90	Assess cost of chemical heat pipe solar system
91	Document solar system results for chemical heat pipe concept
92	**4. Address well field management issues (first look)**
93	Shell picks one case for analysis by Sandia
94	Develop finite element model for well heat extraction
95	Analyze freeze issues for startup and shutdown (if molten salt selected by Shell)
96	Develop simplified well model, e.g. To=f(Ti, flow rate, Twell)
97	Connect simple well model into a well field model
98	Analyze solar system performance/cost for variable temperature operation
99	Analyze startup and shutdown strategies
100	Document results of well field management (incl. suggestions for future analysis)
101	**5. Collect solar resource and geographical data for Shell sites**
102	**6. Assess environmental benefits of using solar energy (air, water, land)**
103	Shell defines baseline non-solar system(s) for comparison
104	Analyze baseline system(s) impacts
105	Analyze solar impact using 1 Shell case from objective 4
106	Document comparative environmental benefits
107	**7. Develop recommendations for next step**
108	Evalute prior analysis to identify promising options
109	Recommend concepts worth pursuing & sources of industrial support
110	Develop scoping-level description of a full-scale project
111	Identify areas needing further investigation/experimentation
112	**Develop recommendations for a small demonstration project**
113	Develop down hole demo options
114	Develop solar system demo options
115	Estimate cost and performance of demo concepts
116	Identify issues/tradeoffs among options
117	Estimate resources for small demonstration project
118	Document small demo options and Sandia participation
119	**8. Evaluate and report findings**
120	Progress meeting with Shell
121	Draft report
122	Shell reviews report
123	Final



APPENDIX E: RESULTS OF BRAINSTORMING

Idea	Advantages	Disadvantages	Notes
Electric			
SiC	High power densities	Brittle	No advantage over calrod
Calrod	Simple, durable	Requires large amounts of power	Shell is using this – no need for Sandia to continue
Well casing - impedance	No additional parts – use well casing as conductor	Impedance small- need lots of current, well casing can crack	Commercially done – may be worth further investigation.
Well casing - inductance	No additional parts except for coils every x feet.	Well casing can crack, power units are water-cooled	Eff as high as 80%! Cost inquiry to one company but no reply.
Electric discharge		Not known how this would work.	
Nuclear			
Isotope thermal source	Reliable, predictable	Waste disposal	Zero chance of public acceptance.
Optical			
Fiber Optic – direct solar	No freezing issues	Power densities too low, not efficient	Looks like low power apps – drop.
Fiber Optic – laser	No freezing issues	Power densities too low, hole not straight, not efficient	Max eff about 50%, power nowhere near 230 kW – drop.
Fiber Optic – electric light	No freezing issues	Power densities too low, not efficient	Looks like low power apps – drop.
Direct laser/absorber	No freezing issues	Power densities too low, hole not straight, not efficient	Max eff about 50%, power nowhere near 230 kW- drop.
Chemical			
Methane reforming	Lower thermal losses	Many unknowns	This would be a major development program.
Methane combustion	No freezing issues	Not solar	High efficiency
Well product combustion	No freezing issue	Not solar	High efficiency
Solid rocket fuel	No freezing issue	Don't see advantage over methane.	Expensive

Acoustic			
Thermoacoustic transmission	No freezing issues	Noisy, low power?	
Microwave			
Surface gen/ waveguide	No freezing issues	Hole not straight	Low efficiency, expensive
Thermal			
Steam	Minimal freezing issues	2-phase flow	
Molten salt	Can work with solar	Freezing issues	High interest
Heat-pipes	Isothermal operating conditions	Complex, expensive, sodium	Not practical here
Engineered fluid	Find a fluid that will work at these temperatures, but will not freeze	Much work has been done on this – not likely in near term.	
Salt/water mix	No freezing issues	Cumbersome?	
Mechanical			
Surface motor/friction downhole	No freezing issues	Big clutch, wearing issues	
Vibrator	No freezing issues	Crumble the hole?	

APPENDIX F: MATHCAD MODEL

Solution for temperatures and flux in counterflow injection of salt into well, radiative coupling to bore, 1-D stacked-disk reservoir, limited source power. The required variable mass flow rate is accounted for in the energy eqn, but not in its effect on the film coefficients -- OK for salt but less so for gas.

1. DATA INPUT & SETUP:

$Q := 300 \cdot kW$ **heat source capacity**

$tw_0 := (50 + 273) \cdot K$ **initial overburden temp.**

$tw_1 := (50 + 273) \cdot K$ **initial shale temp.**

$Mfix := 0$ **1 means fix Mdot at the following value: 0 means vary Mdot to fix heat delivered at Q**

$Ts := (565 + 273) \cdot K$ **source temperature; max for nitrate is 565 C**

$Mdotf := 12 \cdot \frac{kg}{sec}$

RESERVOIR AND WELL DIMENSIONS

$z_{shale} := 800 \cdot ft$ **shale interval thickness**

$z_{overburden} := 800 \cdot ft$ **overburden thickness**

$zmax := z_{shale} + z_{overburden}$ **distance from well bottom to well head**

$NW := 100$ **Well bore integration steps** $\Delta z := \frac{zmax}{NW}$ $NWI := \frac{z_{shale}}{\Delta z}$

$R1 := 6 \cdot in$

$R2 := 15.75 \cdot ft$

$\alpha := 6.6 \cdot 10^{-3} \cdot \frac{cm^2}{sec}$ $k := 3.25 \cdot 10^{-3} \cdot \frac{cal}{cm \cdot sec \cdot K}$ $k = 0.014 \frac{watt}{cm \cdot K}$ $CRp := \frac{k}{\alpha}$

$NR := 20$ $tmax := 1752 \cdot hr$ $Nt := 219$ $\Delta t := \frac{tmax}{Nt}$ $Nsfrq := 3$ **Store frequency**

$\Delta t = 8 hr$ $Npts := \frac{Nt}{Nsfrq}$ $Npts = 73$ $i := 1 .. Npts$ $time_i := i \cdot Nsfrq \cdot \Delta t$

$CP1 := \left(\frac{R2}{R1}\right)^{\frac{1}{NR}}$ **variable grid parameter**

$mm := 0 .. NR$ $r_{mm} := R1 \cdot (CP1)^{mm}$ **set up grid** $\Delta r_0 := r_1 - r_0$

$mm := 1 .. NR$ $\Delta r_{mm} := r_{mm} - r_{mm-1}$ $\varepsilon_{mm-1} := \frac{\Delta r_{mm-1}}{\Delta r_{mm}}$ $\Delta r_1 = 1.13 in$ $\Delta r_{NR} = 2.495 ft$

$\varepsilon_{NR} := 1$ $qbar := \frac{(\Delta r_1)^2}{k} \cdot \left(\frac{1}{R1} - \frac{2}{\Delta r_1}\right)$

$mm := 0..NR$

$$E_{mm} := -2\cdot\varepsilon_{mm} - \frac{(\Delta r_{mm})^2}{\alpha\cdot\Delta t} + (1-\varepsilon_{mm})\cdot\frac{\Delta r_{mm}}{2\cdot r_{mm}} \qquad Ep_{mm} := -\frac{(\Delta r_{mm})^2}{\alpha\cdot\Delta t}$$

$$Rp_{mm} := \varepsilon_{mm}\cdot\left(\frac{\Delta r_{mm}}{2\cdot r_{mm}} + \frac{2\cdot\varepsilon_{mm}}{1+\varepsilon_{mm}}\right) \qquad Rm_{mm} := \frac{\Delta r_{mm}}{2\cdot r_{mm}} - \frac{2\cdot\varepsilon_{mm}}{1+\varepsilon_{mm}}$$

SALT PROPERTIES

$\rho_{salt} := 1724\frac{kg}{m^3}$

$Cp := 1542\cdot\frac{joule}{kg\cdot K}$ **60%NaNO3/40%KNO3 heat cap at 575C**

$\mu := (0.0011)\cdot Pa\cdot sec$ **Absolute viscosity**

$k := 0.551\cdot\frac{watt}{m\cdot K}$ **Thermal conductivity** $Pr := 3.08$

<u>The following definitions are done first for the overburden and then for the shale interval</u>

$D_1 := 1.38\cdot in$ **} downcomer**
$D_2 := 1.66\cdot in$ **pipe**
-- insulation
$D_3 := 1.995\cdot in$ **} upcomer inner pipe**
$D_4 := 2.375\cdot in$
$D_5 := 2.992\cdot in$ **} upcomer outer pipe**
$D_6 := 3.50\cdot in$
-- insulation
$D_7 := 11\cdot in$ **} string outer pipe**
$D_8 := 11.1\cdot in$
$D_9 := 2\cdot R1$ **casing inner diameter, matches reservoir inner diameter, same for shale**

$i := 1..7 \quad t_i := \frac{D_{i+1} - D_i}{2}$

$i := 1..9 \quad A_i := \pi\cdot D_i$

$Auo_0 := A_5$ **upcomer annulus outer area per unit depth**

$Aui_0 := A_4$ **upcomer annulus inner area per unit depth**

$Ad_0 := A_1$ **downcomer area per unit depth**

$Axu_0 := 0.25\pi\cdot\left[\left(D_5\right)^2 - \left(D_4\right)^2\right]$ **upcomer x-section**

$Axd_0 := 0.25\pi\cdot\left(D_1\right)^2$ **downcomer x-section**

PIPE PROPERTIES IN THE OVERBURDEN INTERVAL

$$\sigma := 0.4756 10^{-12}\cdot\frac{BTU}{ft^2\cdot sec\cdot R^4}$$

$kod_{insul} := 0.015\frac{BTU}{hr\cdot ft\cdot R}$ $kou_{insul} := 0.067\frac{BTU}{hr\cdot ft\cdot R}$ **OTSI Thermal Tube 3-H (670 F, includes coupling)**

$k_{ss304} := 13\cdot\frac{BTU}{hr\cdot ft\cdot R}$ **Approx., 1000 F**

$\varepsilon_p := 0.73$ $\varepsilon_w := 0.82$ **injection pipe & well casing emissivities; 304 ss, 0.73, 42 h/520C; smooth oxidized iron, 0.82 (Marks, p 4-68)**

$$U_{d\_insul} := \frac{2\cdot\pi}{A_4\cdot\left(\frac{\ln\left(\frac{A_2}{A_1}\cdot\frac{A_4}{A_3}\right)}{k_{ss304}} + \frac{\ln\left(\frac{A_3}{A_2}\right)}{kod_{insul}}\right)}$$

$$U_{u\_insul} := \frac{2\cdot\pi}{A_5\cdot\left(\frac{\ln\left(\frac{A_6}{A_5}\cdot\frac{A_8}{A_7}\right)}{k_{ss304}} + \frac{\ln\left(\frac{A_7}{A_6}\right)}{kou_{insul}}\right)}$$

$$UR_0 := \frac{\sigma\cdot K^3}{\left[\frac{1}{\varepsilon_p} + \left(\frac{1}{\varepsilon_w} - 1\right)\cdot\frac{A_8}{A_9}\right]}\cdot\frac{A_8}{A_5}$$ **(not a conductance until x [Tp^4-Tw^4]/[Tu-Tw])**

FLUID HEAT TRANSFER PRELIMINARIES IN THE OVERBURDEN INTERVAL

$rhu_0 := \frac{Axu_0}{Auo_0 + Aui_0}$ $rhu_0 = 0.154in$ **upcomer hydraulic radius** $rhd_0 := 0.25 D_1$

$\Delta Ts0 := \frac{Ts - tw_1}{K}$ $Mdot := \frac{Q}{Cp\cdot\Delta Ts0\cdot K}$ $Mdot = 0.378kg\,sec^{-1}$ **t = 0 estimate, used if constant heat delivery option is chosen**

$Mdot := \mathrm{if}(Mfix, Mdotf, Mdot)$

$MdotCp := Mdot\cdot Cp$ $MdotCp = 582.524\frac{watt}{K}$ $Gu_0 := \frac{Mdot}{Axu_0}$ $Gd_0 := \frac{Mdot}{Axd_0}$

$Reu_0 := 4 \cdot rhu_0 \cdot Gu_0 \cdot \frac{1}{\mu}$ $Reu_0 = 3.208 \times 10^3$ $Red_0 := D_1 \cdot \left(Gd_0 \cdot \frac{1}{\mu} \right)$ $Red_0 = 1.247 \times 10^4$

From Kays & London, p 116, 127-132, for turbulent flow in tubes & concentric tubes:

$Nu_{uo} := 80 \cdot \left(\frac{Reu_0}{10^4} \right)^{0.85}$ **rough estimate for upcomer outer wall Nusselt number**

$Nu_{ui} := Nu_{uo}$ **...and upcomer inner wall Nusselt number**

$Nu_d := 60 \cdot \left(\frac{Red_0}{10^4} \right)^{0.85}$ **...and downcomer Nusselt number**

$h_{uo} := \frac{k \cdot Nu_{uo}}{4 \cdot rhu_0}$ $h_{ui} := \frac{k \cdot Nu_{ui}}{4 \cdot rhu_0}$ $h_d := \frac{k \cdot Nu_d}{D_1}$

$Ui := \frac{1}{\left(\frac{A_1}{h_d \cdot A_4} + \frac{1}{h_{ui}} \right) + \frac{1}{U_{d\_insul}}}$ **conductance between inner and outer salt streams**

$Uo_0 := \frac{1}{\frac{1}{h_{uo}} + \frac{1}{U_{u\_insul}}}$ **conductance between outer stream and well casing (missing radiation term, taken care of later)**

$UAdZsMCi_0 := \frac{Ui \cdot Aui_0 \cdot \Delta z}{MdotCp}$ $AdZsMCo_0 := \frac{Auo_0 \cdot \Delta z}{MdotCp}$

Repeating for the shale interval...

$D_1 := 1.38 \cdot in$
} downcomer pipe
$D_2 := 1.66 \cdot in$
-- insulation

$D_3 := 1.995 \cdot in$
} upcomer inner pipe
$D_4 := 2.375 \cdot in$

$D_5 := 2.992 \cdot in$
} upcomer outer pipe
$D_6 := 3.50 \cdot in$
-- insulation

$D_7 := 4.0 \cdot in$
} string outer pipe
$D_8 := 4.5 \cdot in$

$D_9 := 2 \cdot R1$ **casing inner diameter, same as reservoir inner diameter, same for overburden**

$i := 1..7 \quad t_i := \dfrac{D_{i+1} - D_i}{2}$

$i := 1..9 \quad A_i := \pi \cdot D_i$

$Auo_1 := A_5$ **upcomer annulus outer area per unit depth**

$Aui_1 := A_4$ **upcomer annulus inner area per unit depth**

$Ad_1 := A_1$ **downcomer area per unit depth**

$Axu_1 := 0.25\pi \cdot \left[(D_5)^2 - (D_4)^2 \right]$ **upcomer x-section**

$Axd_1 := 0.25\pi \cdot (D_1)^2$ **downcomer x-section**

PIPE PROPERTIES FOR THE SHALE INTERVAL

$ksd_{insul} := 0.015 \dfrac{BTU}{hr \cdot ft \cdot R} \quad ksu_{insul} := 13 \cdot \dfrac{BTU}{hr \cdot ft \cdot R}$ **OTSI Thermal Tube 3-H (670 F, includes coupling)**

$k_{ss304} := 13 \cdot \dfrac{BTU}{hr \cdot ft \cdot R}$ **Approx., 1000 F**

$\varepsilon_p := 0.73 \quad \varepsilon_w := 0.82$ **injection pipe & well casing emissivities; 304 ss, 0.73, 42 h/520C; smooth oxidized iron, 0.82 (Marks, p 4-68)**

$$U_{d\_insul} := \frac{2 \cdot \pi}{A_4 \cdot \left(\dfrac{\ln\left(\dfrac{A_2}{A_1} \cdot \dfrac{A_4}{A_3}\right)}{k_{ss304}} + \dfrac{\ln\left(\dfrac{A_3}{A_2}\right)}{ksd_{insul}} \right)}$$

$$U_{u\_insul} := \frac{2 \cdot \pi}{A_5 \cdot \left(\dfrac{\ln\left(\dfrac{A_6}{A_5} \cdot \dfrac{A_8}{A_7}\right)}{k_{ss304}} + \dfrac{\ln\left(\dfrac{A_7}{A_6}\right)}{ksu_{insul}} \right)}$$

$$UR_1 := \frac{\sigma \cdot K^3}{\left[\dfrac{1}{\varepsilon_p} + \left(\dfrac{1}{\varepsilon_w} - 1 \right) \cdot \dfrac{A_8}{A_9} \right]} \cdot \frac{A_8}{A_5}$$ **(not a conductance until x [Tp^4-Tw^4]/[Tu-Tw]**

FLUID HEAT TRANSFER PRELIMINARIES FOR THE SHALE INTERVAL

$rhu_1 := \dfrac{Axu_1}{Auo_1 + Aui_1} \quad rhu_1 = 0.154in$ **upcomer hydraulic radius**

$rhd_1 := 0.25 D_1$

$Gu_1 := \dfrac{Mdot}{Axu_1} \quad Gd_1 := \dfrac{Mdot}{Axd_1}$

$Reu_1 := 4 \cdot rhu_1 \cdot Gu_1 \cdot \frac{1}{\mu}$ $Reu_1 = 3.208 \times 10^3$ $Red_1 := D_1 \cdot \left(Gd_1 \cdot \frac{1}{\mu} \right)$ $Red_1 = 1.247 \times 10^4$

From Kays & London, p 116, 127-132, for turbulent flow in tubes & concentric tubes:

$Nu_{uo} := 80 \cdot \left(\frac{Reu_1}{10^4} \right)^{0.85}$ **rough estimate for upcomer outer wall Nusselt number**

$Nu_{ui} := Nu_{uo}$ **...and upcomer inner wall Nusselt number**

$Nu_d := 60 \cdot \left(\frac{Red_1}{10^4} \right)^{0.85}$ **...and downcomer Nusselt number**

$h_{uo} := \frac{k \cdot Nu_{uo}}{4 \cdot rhu_1}$ $h_{ui} := \frac{k \cdot Nu_{ui}}{4 \cdot rhu_1}$ $h_d := \frac{k \cdot Nu_d}{D_1}$ $h_{uo} = 1.07 \times 10^3 \frac{watt}{m^2 \cdot K}$

$Ui := \frac{1}{\left(\frac{A_1}{h_d \cdot A_4} + \frac{1}{h_{ui}} \right) + \frac{1}{U_{d\_insul}}}$ **conductance between inner and outer salt streams**

$Uo_1 := \frac{1}{\frac{1}{h_{uo}} + \frac{1}{U_{u\_insul}}}$ **conductance between outer stream and well casing (missing radiation term)**

$UAdZsMCi_1 := \frac{Ui \cdot Aui_1 \cdot \Delta z}{MdotCp}$ $AdZsMCo_1 := \frac{Auo_1 \cdot \Delta z}{MdotCp}$

2. SOLVING THE CONJUGATE WELL/RESERVOIR EQUATIONS $Tsc := \frac{Ts}{K} - 273$

j=0: overburden; j=1: shale

$j := 0..1$ $twc_j := \frac{tw_j}{K} - 273$ **Program result is unitless implicit in deg C**

$Ufact0_j := UAdZsMCi_j$ $Afact0_j := AdZsMCo_j$ $qb_j := qbar \cdot \frac{Auo_j}{2 \cdot \pi \cdot R1}$ $Mfactmin := \frac{Mdot}{3 \cdot \frac{kg}{sec}}$

$i := 0..NW$ $Twc_i := if(i > NWI, twc_0, twc_1)$
$Tw_i := if(i > NWI, tw_0, tw_1)$
$Z_i := i \cdot \Delta z$

T0 : inner salt
T1 : outer salt
T2 : position, z
T3 : flux out, riser OD area/ft basis

```
M := | I1 ← 0
     | I2 ← 0
     | Mfact ← 1
     | for i ∈ 0.. NW
     |   | Told_i ← Tw_i / K
     |   | for mm ∈ 0.. NR
     |   |   Toldc_(mm,i) ← Twc_i
     | for itime ∈ 1.. Nt
     |   | KL ← -1
     |   | change ← 0.1
     |   | while change > 0.01
     |   |   | KL ← KL + 1
     |   |   | for L ∈ 0.. 2
     |   |   |   | T0 ← 100  if L < 1
     |   |   |   | T1 ← 200  if L < 2
     |   |   |   | i ← 1
     |   |   |   | fact ← 1  if L = 0
     |   |   |   | fact ← 1.001  if L = 1
     |   |   |   | (fact ← 1 + ((Tsc - T0)/(T1 - T0))·0.001)  if L = 2
     |   |   |   | Tguess ← Tsc  if KL = 0
     |   |   |   | T_(0,0) ← Tguess·fact
     |   |   |   | change ← |fact - 1|  if L = 2
     |   |   |   | Tguess ← T_(0,0)  if L = 2
     |   |   |   | T_(1,0) ← T_(0,0)
     |   |   |   | while i ≤ NW
     |   |   |   |   | j ← if(i > NWI, 0, 1)
     |   |   |   |   | T_(0,i) ← (T_(0,i-1) - T_(1,i-1))·UAdZsMCi_j·Mfact + T_(0,i-1)
     |   |   |   |   | x ← Toldc_(0,i)
     |   |   |   |   | T_pipe ← root[Uo_j·(T_(1,i-1) - x) - UR_j·[(x + 273)^4 - (Told_i)^4], x]
     |   |   |   |   | Utoto ← 1 / [ 1/Uo_j + (T_pipe - Toldc_(0,i)) / (UR_j·[(T_pipe + 273)^4 - (Told_i)^4]) ]
     |   |   |   |   | UAdZsMCo ← AdZsMCo_j·Mfact·Utoto
     |   |   |   |   | T_(1,i) ← [(T_(0,i-1) - T_(1,i-1))·UAdZsMCi_j·Mfact + T_(1,i-1)] - (T_(1,i-1) - Toldc_(0,i))·UAdZsMCo
     |   |   |   |   | T_(2,i) ← (T_(1,i) - Toldc_(0,i))·Utoto/(kg sec^-3 K^-1)  if L = 2
     |   |   |   |   | dummy ← root[Uo_j·(T_(1,i-1) - x) - UR_j·[(x + 273)^4 - (Told_i)^4], x]
     |   |   |   |   | i ← i + 1
     |   |   |   | T0 ← T_(0,NW)  if L = 0
     |   |   |   | T1 ← T_(0,NW)  if L = 1
     |   | T_(2,0) ← T_(2,1)
```

```
Mfact ← (Tsc − T_{1,NW}) / ΔTs0
Mfact ← Mfactmin  if  Mfact < Mfactmin
Mfact ← 1  if  Mfix = 1
for  i ∈ 0.. NW
    j ← if(i > NWI, 0, 1)
    for  mm ∈ 0.. NR
        u0_mm ← Toldc_{mm,i}
    for  mm ∈ 0.. NR
        L_mm ← −Rm_mm
        D_mm ← E_mm
        U_mm ← Rp_mm
        f_mm ← Ep_mm·u0_mm
    L_0 ← 0
    L_NR ← 2
    U_0 ← 2
    U_NR ← 0
    D_0 ← D_0 + qb_j·[4·UR_j·(Told_i)^3]
    f_0 ← f_0 + qb_j·[T_{2,i}·watt/(m^2·K) + 4·UR_j·(Told_i)^3·u0_0]
    for  mm ∈ 0.. NR − 1
        D_{mm+1} ← D_{mm+1} − U_mm·L_{mm+1}/D_mm
        f_{mm+1} ← f_{mm+1} − f_mm·L_{mm+1}/D_mm
    u_NR ← f_NR / D_NR
    for  mm ∈ NR − 1.. 0
        u_mm ← (f_mm − U_mm·u_{mm+1}) / D_mm
    for  mm ∈ 0.. NR
        mp ← mm + 3
        T_{mp,i} ← u_mm
for  i ∈ 0.. NW
    Told_i ← (T_{3,i} + 273)
    T_{NR+4,i} ← Mfact
    for  mm ∈ 0.. NR
        Toldc_{mm,i} ← T_{mm+3,i}
I1 ← I1 + 1
I2 ← I2 + 1  if  I1 = Nsfrq
M_I2 ← T  if  I1 = Nsfrq
I1 ← 0  if  I1 = Nsfrq
M
```

3. ENERGY BALANCE CHECK & RESULTS DISPLAYS....AT: $It := 73$

recap conditions:

$tmax = 1.752 \times 10^{3}\,hr$ $Nt = 219$

$\Delta t = 8\,hr$ $Nsfrq = 3$ $Npts = 73$

$Q = 3 \times 10^{5}\,watt$ **desired injection rate**

Mi=results at time step i*Nsfrq
Mi row 0 : inner salt T
Mi row 1 : outer salt T
Mi row 2 : flux out, basis area=1ft of riser OD
Mi row >3 : reservoir T
Columns: bottom to top

$Tw_0 - 273 \cdot K = 50K$ **deg C overburden (wall) temp.**

$Tw_1 - 273 \cdot K = 50K$ **deg C shale (wall) temp.**

$Tsc = 565$ **deg C source temperature; max for nitrate is 565 C**

$kod_{insul} = 0.015 \frac{BTU}{hr \cdot ft \cdot R}$ $kou_{insul} = 0.067 \frac{BTU}{hr \cdot ft \cdot R}$

$ksd_{insul} = 0.015 \frac{BTU}{hr \cdot ft \cdot R}$ $ksu_{insul} = 13 \frac{BTU}{hr \cdot ft \cdot R}$

POWER BALANCE CHECK, INSTANTANEOUS

$AdZ_0 := Auo_0 \cdot \Delta z$ $AdZ_1 := Auo_1 \cdot \Delta z$

```
Qw := | i ← 1
      | Q0 ← 0
      | Q1 ← 0
      | while i ≤ NW
      |   | j ← if(i > NWI, 0, 1)
      |   | Qj ← (M_It)_{2,i-1} · AdZ_j / m^2 + Qj
      |   | i ← i + 1
      | Q
```

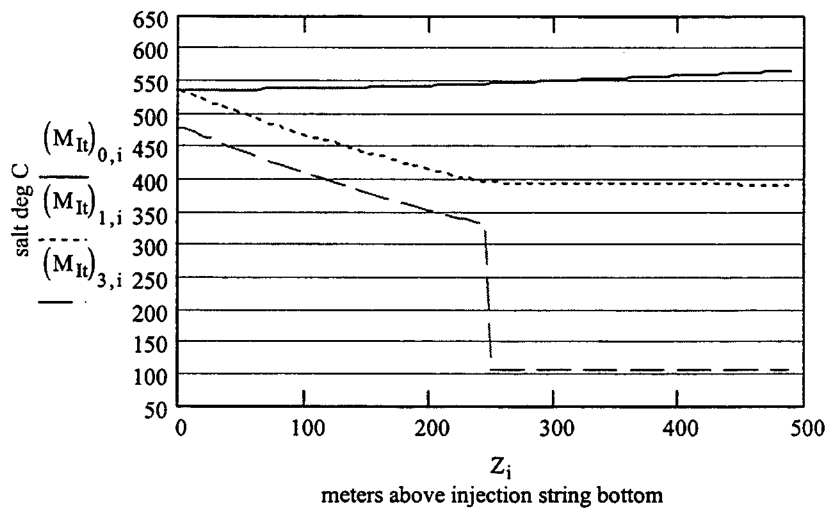
$\frac{MdotCp}{(M_{It})_{NR+4,1}} \cdot K \cdot \left[Tsc - (M_{It})_{1,NW}\right] = 3 \times 10^{5}\,watt$

$(Qw_0 + Qw_1) \cdot watt = 2.928 \times 10^{5}\,watt$

$(M_{It})_{1,NW} = 391.584$

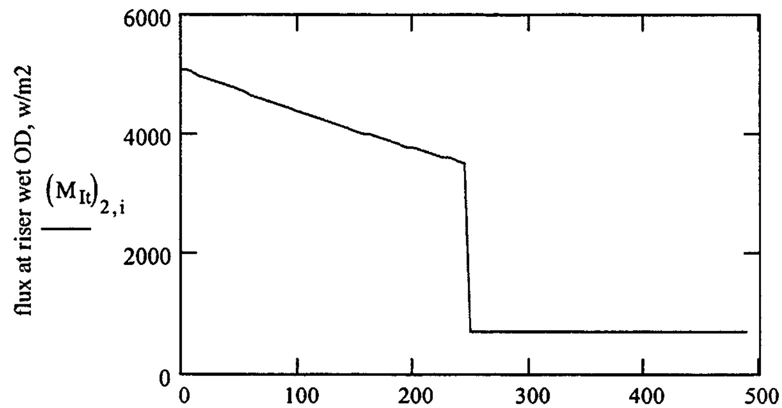
$\left[Tsc - (M_{It})_{1,NW}\right] = 173.416$

PLOTS tmax = 1.752×10^{3} hr Nt = 219 Nsfrq = 3 Npts = 73 It = 73 i := 0.. NW



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing

$z_{shale} = 243.84m$

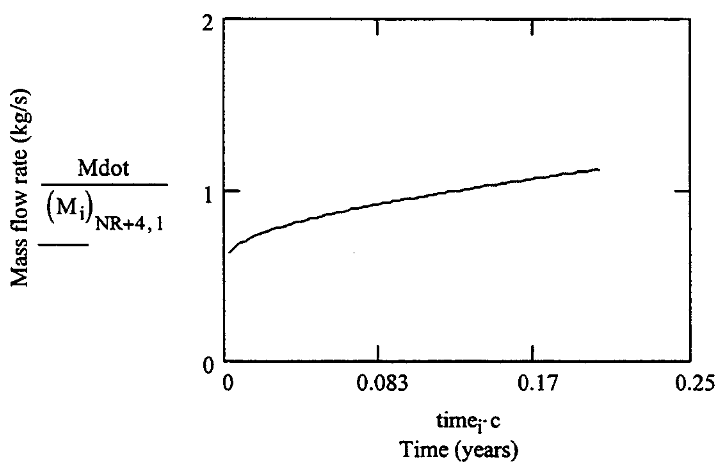


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 4.428\times 10^{4} \\ 2.485\times 10^{5} \end{pmatrix}$$

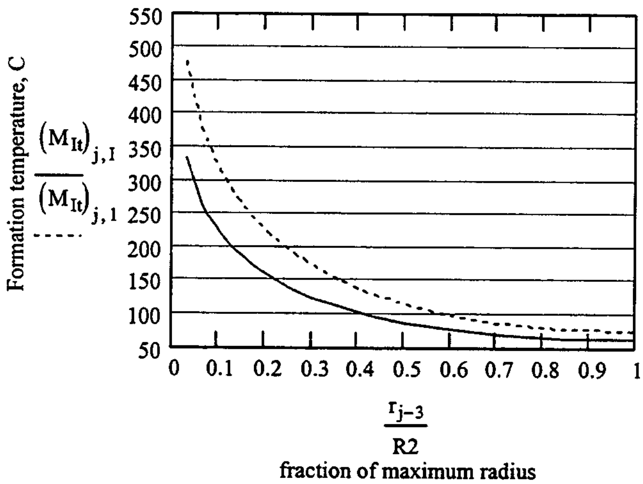
i := 1.. Npts

$$c := \frac{1}{3.15\cdot 10^{7}}$$

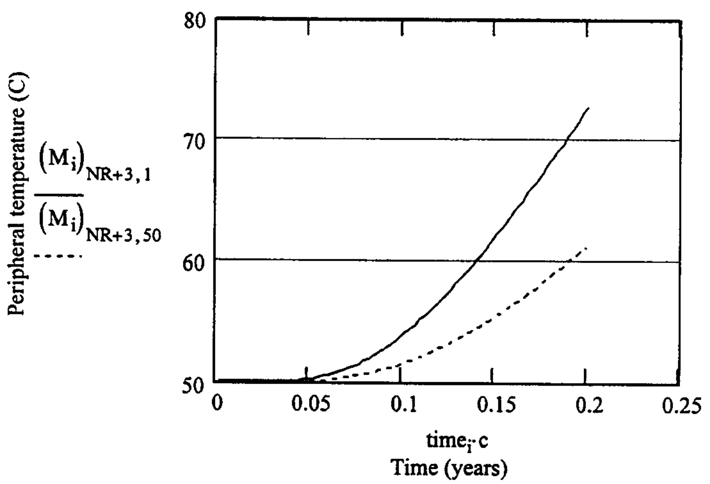


$I := 50$ **(# steps above well bottom)** $j := 3 .. NR + 3$

tmax = 1.752×10^3 hr Nt = 219 Nsfrq = 3 Npts = 73 It = 73



$i := 1 .. Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK

It = 73 $\quad Is := if(It > 1, 1, 0) \quad Itm := if(It > 1, It - 1, 1)$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot K \cdot \sum_{i=1}^{Itm} \left[\frac{Tsc - \frac{(M_i)_{1,NW} + (M_{i+Is})_{1,NW}}{2}}{(M_i)_{NR+4,1}} \right]$$

Based on salt ΔT and MdotCp;

$$Ein := Ein + \frac{MdotCp}{(M_{It})_{NR+4,1}} \cdot Nsfrq \cdot \Delta t \cdot K \cdot \left[Tsc - \left[1.5 \cdot (M_{It})_{1,NW} - 0.5 \cdot (M_{Itm})_{1,NW} \right] \right]$$

$Ein = 1.885 \times 10^{12}$ joule

$$\Delta ER := CRp\cdot\Delta z\cdot\pi\cdot K\cdot\sum_{j=0}^{NR-1}\left[\left(r_{j+1}\right)^2-\left(r_j\right)^2\right]\cdot\sum_{i=0}^{NW}\left[\frac{\left(M_{It}\right)_{j+3,i}+\left(M_{It}\right)_{j+4,i}}{2}-Twc_i\right]$$

Based on reservoir ΔTs

"Ein" sum based on fact that salt temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

$\Delta ER = 1.79\times 10^{12}\,\text{joule}$ $\quad \frac{\Delta ER}{Ein} - 1 = -0.05$

$$Ew := \begin{array}{|l} Q_0 \leftarrow 0 \\ Q_1 \leftarrow 0 \\ \text{for } I \in 1..It \\ \quad \begin{array}{|l} i \leftarrow 1 \\ \text{while } i \le NW \\ \quad \begin{array}{|l} j \leftarrow \text{if}(i > NWI, 0, 1) \\ Q_j \leftarrow \left[\frac{\left(M_I\right)_{(2,i-1)}+\left(M_I\right)_{(2,i)}}{2}\right]\cdot\frac{AdZ_j}{m^2}+Q_j \\ i \leftarrow i+1 \end{array} \end{array} \\ Q \end{array}$$

Based on radiative flux

$\left(Ew_0 + Ew_1\right)\cdot watt\cdot Nsfrq\cdot\Delta t = 1.828\times 10^{12}\,\text{joule}$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.131$ **overburden fraction**

$\frac{\left(Ew_0 + Ew_1\right)\cdot watt\cdot Nsfrq\cdot\Delta t}{Ein} - 1 = -0.03$

4. Finally, estimate pump pressure, at time step It, using ME Hdbk & μ(T)...

j=0: overburden; j=1: shale $\quad \varepsilon p := 150\cdot 10^{-6}\cdot ft$ **(pipe roughness)**

$tmax = 1.752\times 10^3\,hr$ $\quad Nt = 219$ $\quad Nsfrq = 3$ $\quad Npts = 73$ $\quad It = 73$ $\quad Mf := \left(M_{It}\right)_{NR+4,1}$

$$
\begin{aligned}
\Delta P := \; & \Delta P_0 \leftarrow 0 \\
& \Delta P_1 \leftarrow 0 \\
& \text{for } i \in 1..NW \\
& \quad j \leftarrow \text{if}(i > NWI, 0, 1) \\
& \quad Td \leftarrow \left(M_{It}\right)_{0,i} \\
& \quad Tu \leftarrow \left(M_{It}\right)_{1,i} \\
& \quad RNd \leftarrow \frac{Red_j}{Mf} \cdot \frac{\mu}{\left(0.02141 - 1.106210^{-4} \cdot Td + 2.0645810^{-7} \cdot Td^2 - 1.3134810^{-10} \cdot Td^3\right) \cdot Pa \cdot sec} \\
& \quad RNu \leftarrow \frac{Reu_j}{Mf} \cdot \frac{\mu}{\left(0.02141 - 1.106210^{-4} \cdot Tu + 2.0645810^{-7} \cdot Tu^2 - 1.3134810^{-10} \cdot Tu^3\right) \cdot Pa \cdot sec} \\
& \quad x \leftarrow \frac{0.32}{(RNd)^{0.25}} \text{ if } i = 1 \\
& \quad fd \leftarrow \text{if}\left(RNd < 2000, \frac{64}{RNd}, \text{root}\left(\frac{1}{\sqrt{x}} + 2 \cdot \log\left(\frac{\varepsilon p}{14.8 \cdot rhd_j} + \frac{2.51}{RNd \cdot \sqrt{x}}\right), x\right)\right) \\
& \quad fu \leftarrow \text{if}\left(RNu < 2000, \frac{64}{RNu}, \text{root}\left(\frac{1}{\sqrt{x}} + 2 \cdot \log\left(\frac{\varepsilon p}{14.8 \cdot rhu_j} + \frac{2.51}{RNu \cdot \sqrt{x}}\right), x\right)\right) \\
& \quad \Delta P_0 \leftarrow \frac{\left(\frac{Gd_j}{Mf}\right)^2}{2 \cdot \rho_{salt}} \cdot \frac{fd}{4} \cdot \frac{Ad_j}{Axd_j} \cdot \frac{\Delta z}{Pa} + \Delta P_0 \\
& \quad \Delta P_1 \leftarrow \frac{\left(\frac{Gu_j}{Mf}\right)^2}{2 \cdot \rho_{salt}} \cdot \frac{fu}{4} \cdot \frac{Auo_j + Aui_j}{Axu_j} \cdot \frac{\Delta z}{Pa} + \Delta P_1 \\
& \Delta P
\end{aligned}
$$

$\Delta P_0 \cdot Pa = 20.631 psi$

$$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$$

$\Delta Pg = 52.125 psi$

$\Delta P_1 \cdot Pa = 22.481 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$$

$P_{pump} = 427.3 watt$

$\Delta ptotal = 95.236 psi$

salt volume per well

$$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$$

mass per well if salt is at 270 C

$$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$$

$M_{salt} = 5.45 \times 10^3 \, lb$

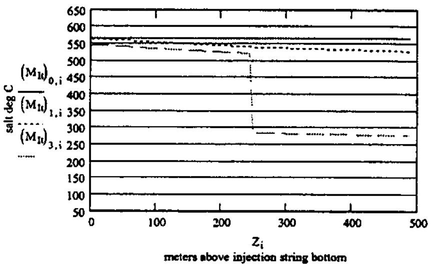
20 wells: $M_{salt} \cdot 20 = 1.09 \times 10^5 \, lb$

APPENDIX G: MOLTEN SALT PARAMETRIC STUDY

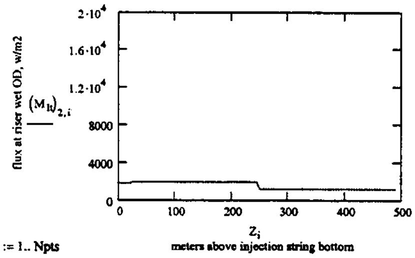
******************** START MOLTEN SALT CASE 1 ********************

PLOTS tmax = 1.872×10^{4} hr Nt = 2.34×10^{3} Nsfrq = 10 Npts = 234 It = 234 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 1.872×10^{4} hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
z_{shale} = 243.84m

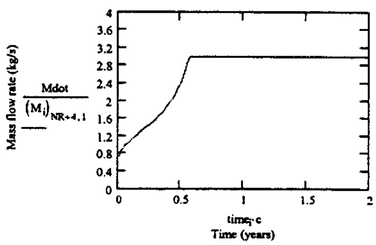


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 6.752\times10^{4} \\ 1.092\times10^{5} \end{pmatrix}$$

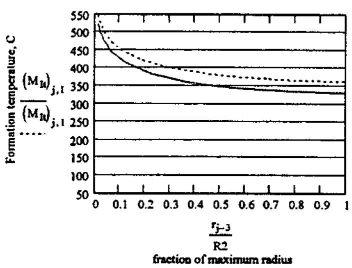
i := 1.. Npts

$$c := \frac{1}{3.15\,10^{7}}$$

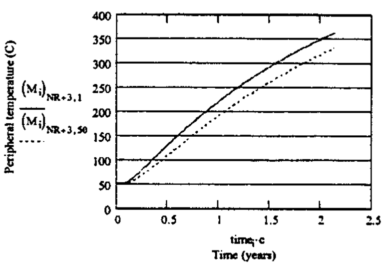


I := 50 **(# steps above well bottom)** j := 3.. NR + 3

tmax = 1.872×10^{4} hr Nt = 2.34×10^{3} Nsfrq = 10 Npts = 234 It = 234



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 131.324 psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 9.406 psi$

$\Delta P_1 \cdot Pa = 128.344 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 3.228 \times 10^3 \, watt$

$\Delta ptotal = 269.074 psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$

$M_{salt} = 5.45 \times 10^3 \, lb$

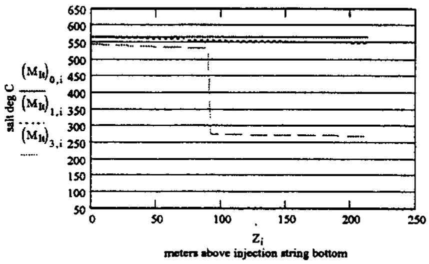
20 wells: $M_{salt} \cdot 20 = 1.09 \times 10^5 \, lb$

******************** **END MOLTEN SALT CASE 1** ***********************

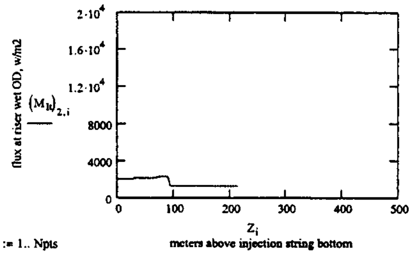
******************** START MOLTEN SALT CASE 2 ********************

PLOTS   tmax = 7.92 × 10³ hr   Nt = 990   Nsfrq = 10   Npts = 99   It = 99   i := 0.. NW

timeplot := It·Nsfrq·Δt   timeplot = 7.92 × 10³ hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
z_{shale} = 91.44m

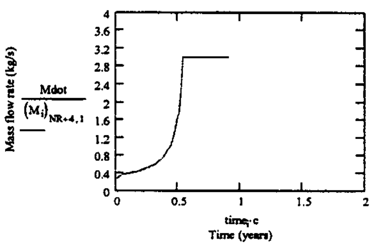


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.753 \times 10^4 \\ 4.495 \times 10^4 \end{pmatrix}$$

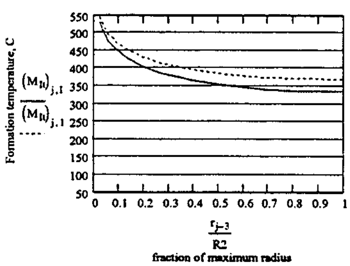
i := 1.. Npts

$$c := \frac{1}{3.15 \cdot 10^7}$$

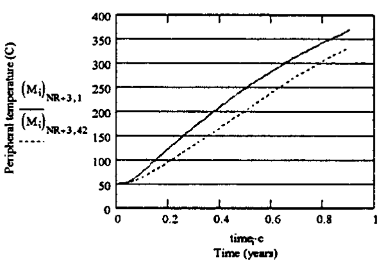


I := 42 **(# steps above well bottom)**   j := 3.. NR + 3

tmax = 7.92 × 10³ hr   Nt = 990   Nsfrq = 10   Npts = 99   It = 99



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 57.441 psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 1.904 psi$

$\Delta P_1 \cdot Pa = 55.952 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 1.383 \times 10^3 \ watt$

$\Delta ptotal = 115.296 psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$

$M_{salt} = 2.384 \times 10^3 \ lb$

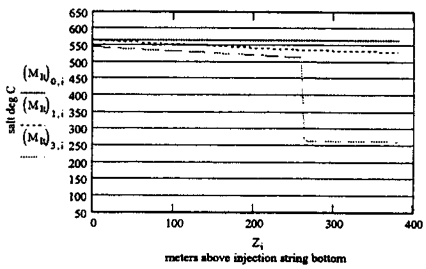
20 wells: $M_{salt} \cdot 20 = 4.769 \times 10^4 \ lb$

******************** **END MOLTEN SALT CASE 2** ***********************

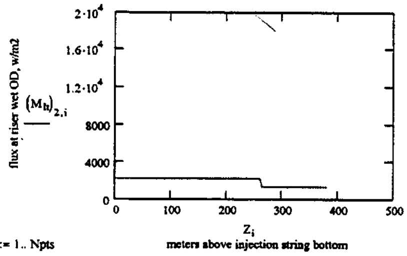
******************* START MOLTEN SALT CASE 3 *******************

PLOTS tmax = 7.2 × 10³ hr   Nt = 900   Nsfrq = 10   Npts = 90   It = 90   i := 0.. NW

timeplot := It·Nsfrq·Δt   timeplot = 7.2 × 10³ hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08m$

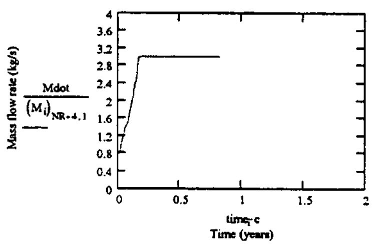


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.604 \times 10^4 \\ 1.316 \times 10^5 \end{pmatrix}$$

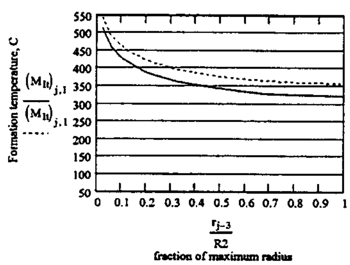
i := 1.. Npts

$$c := \frac{1}{3.15 \cdot 10^7}$$

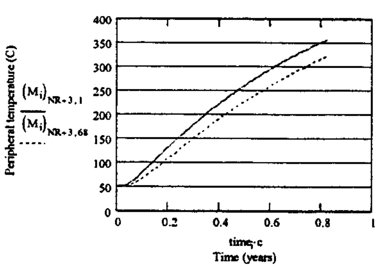


I := 68 **(# steps above well bottom)**   j := 3.. NR + 3

tmax = 7.2 × 10³ hr   Nt = 900   Nsfrq = 10   Npts = 90   It = 90



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 102.589 psi$ $\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$ $\Delta Pg = 6.871 psi$

$\Delta P_1 \cdot Pa = 100.22 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $P_{pump} = 2.516 \times 10^3 \text{ watt}$

$\Delta ptotal = 209.681 psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

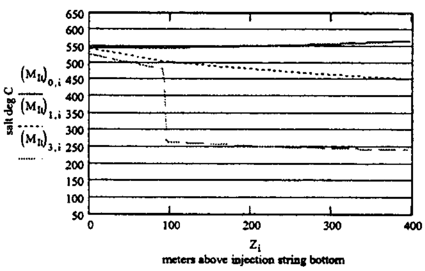
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 4.258 \times 10^3 \text{ lb}$ **20 wells:** $M_{salt} \cdot 20 = 8.516 \times 10^4 \text{ lb}$

******************** **END MOLTEN SALT CASE 3** ***********************

******************** START MOLTEN SALT CASE 4 ****************

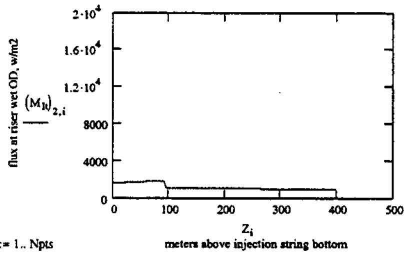
PLOTS tmax = 1.152×10^{4} hr Nt = 1.44×10^{3} Nsfrq = 10 Npts = 144 It = 144 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 1.152×10^{4} hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing

z_{shale} = 91.44m

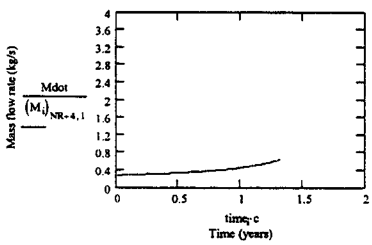


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.286\times10^{4} \\ 3.681\times10^{4} \end{pmatrix}$$

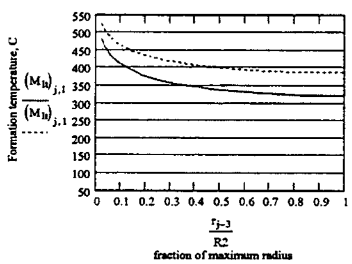
i := 1.. Npts

$$c := \frac{1}{3.15\cdot10^{7}}$$

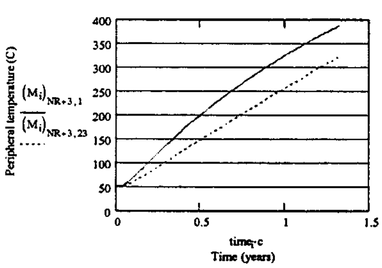


I := 23 **(# steps above well bottom)** j := 3.. NR + 3

tmax = 1.152×10^{4} hr Nt = 1.44×10^{3} Nsfrq = 10 Npts = 144 It = 144



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 5.893psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 22.932psi$

$\Delta P_1 \cdot Pa = 6.369psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 89.434watt$

$\Delta ptotal = 35.195psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$

$M_{salt} = 4.428 \times 10^3 \, lb$

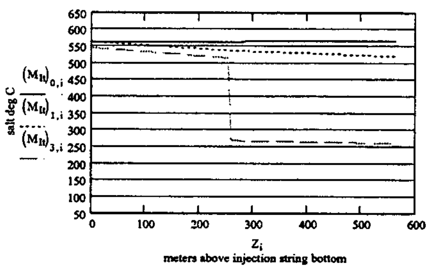
20 wells: $M_{salt} \cdot 20 = 8.856 \times 10^4 \, lb$

******************** **END CASE MOLTEN SALT 4** *****************

******************** START MOLTEN SALT CASE 5 ********************

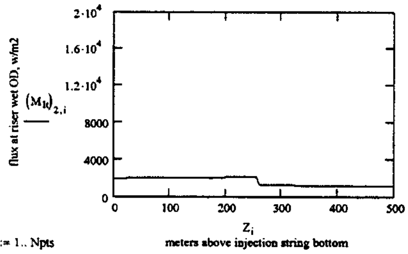
PLOTS $tmax = 7.92 \times 10^3\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 7.92 \times 10^3\,hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing

$z_{shale} = 259.08m$

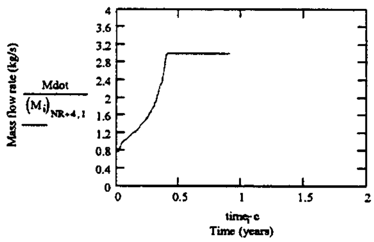


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 8.885 \times 10^4 \\ 1.225 \times 10^5 \end{pmatrix}$$

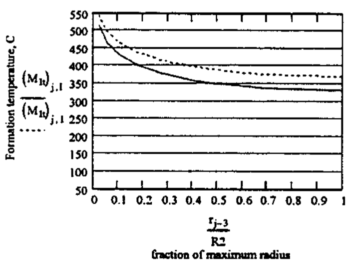
$i := 1..Npts$

$$c := \frac{1}{3.15 \cdot 10^7}$$

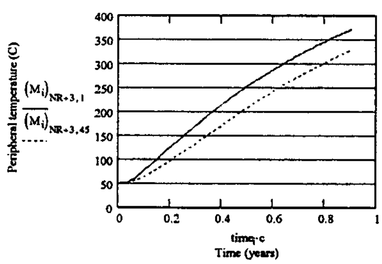


$I := 43$ **(# steps above well bottom)** $j := 3..NR+3$

$tmax = 7.92 \times 10^3\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 151.861 psi$ $\quad \Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$ $\quad \Delta Pg = 13.161 psi$

$\Delta P_1 \cdot Pa = 148.597 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $\quad P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $\quad P_{pump} = 3.763 \times 10^3 \, watt$

$\Delta ptotal = 313.619 psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

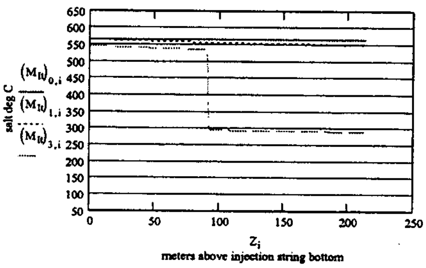
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $\quad M_{salt} = 6.302 \times 10^3 \, lb$ $\quad$ **20 wells:** $M_{salt} \cdot 20 = 1.26 \times 10^5 \, lb$

******************** END MOLTEN SALT CASE 5 ***********************

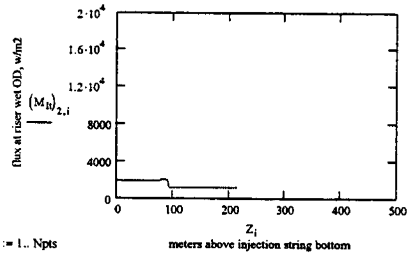
******************** START MOLTEN SALT CASE 6 ********************

PLOTS tmax = 3.312× 10^4 hr Nt = 4.14× 10^3 Nsfrq = 10 Npts = 414 It = 414 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 3.312× 10^4 hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
z_{shale} = 91.44m

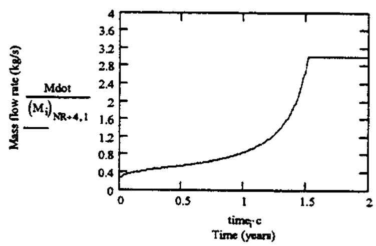


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.521\times 10^4 \\ 4.112\times 10^4 \end{pmatrix}$$

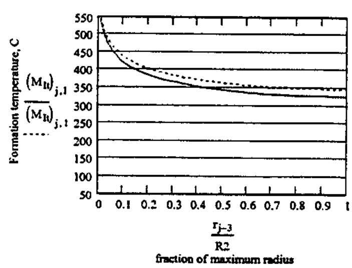
i := 1.. Npts

$$c := \frac{1}{3.15\cdot 10^7}$$

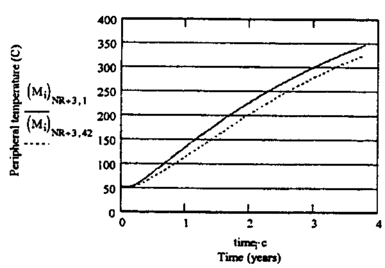


I := 42 **(# steps above well bottom)** j := 3.. NR + 3

tmax = 3.312× 10^4 hr Nt = 4.14× 10^3 Nsfrq = 10 Npts = 414 It = 414



i := 1.. Npts



ΔP

$\Delta P_0 \cdot Pa = 57.44 psi$

$$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$$

$\Delta Pg = 1.754 psi$

$\Delta P_1 \cdot Pa = 55.938 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$$

$P_{pump} = 1.381 \times 10^3 \, watt$

$\Delta ptotal = 115.133 psi$

salt volume per well

$$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$$

mass per well if salt is at 270 C

$$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$$

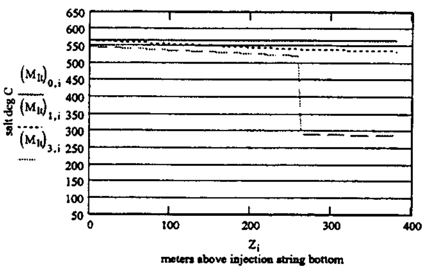
$M_{salt} = 2.384 \times 10^3 \, lb$ **20 wells:** $M_{salt} \cdot 20 = 4.769 \times 10^4 \, lb$

******************** **END MOLTEN SALT CASE 6** ***********************

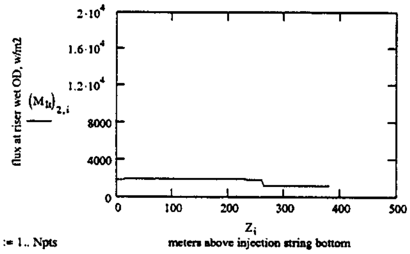
******************** START MOLTEN SALT CASE 7 ********************

PLOTS $tmax = 3.312 \times 10^4 hr$ $Nt = 4.14 \times 10^3$ $Nsfrq = 10$ $Npts = 414$ $It = 414$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 3.312 \times 10^4 hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08m$

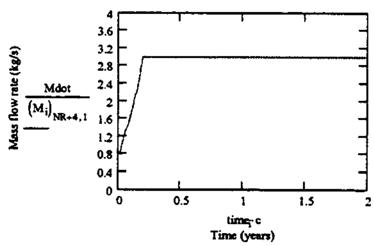


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.35 \times 10^4 \\ 1.144 \times 10^5 \end{pmatrix}$$

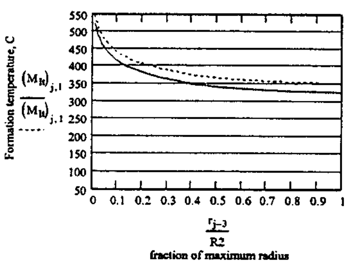
$i := 1..Npts$

$$c := \frac{1}{3.15 \cdot 10^7}$$

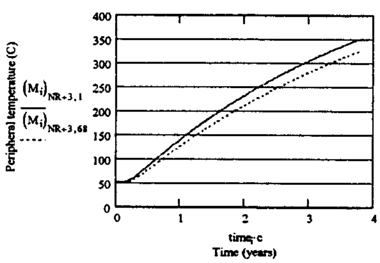


$I := 68$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 3.312 \times 10^4 hr$ $Nt = 4.14 \times 10^3$ $Nsfrq = 10$ $Npts = 414$ $It = 414$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 102.586\,psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$ $\Delta Pg = 6.01\,psi$

$\Delta P_1 \cdot Pa = 100.148\,psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $P_{pump} = 2.504 \times 10^3\,watt$

$\Delta ptotal = 208.744\,psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

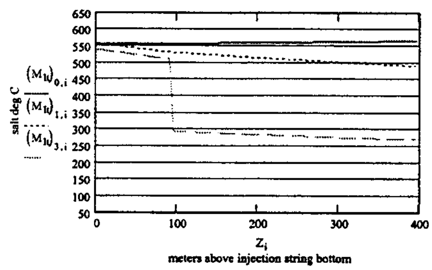
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 4.258 \times 10^3\,lb$ **20 wells:** $M_{salt} \cdot 20 = 8.516 \times 10^4\,lb$

******************** **END MOLTEN SALT CASE 7** ***********************

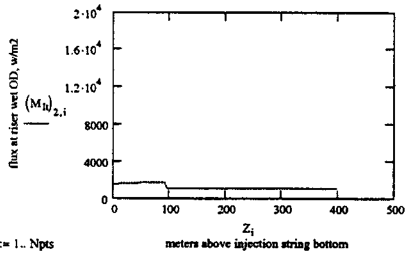
******************** START MOLTEN SALT CASE 8 ********************

PLOTS tmax = 4.896× 10^4 hr Nt = 6.12× 10^3 Nsfrq = 10 Npts = 612 It = 612 i := 0.. NW -

timeplot := It·Nsfrq·Δt timeplot = 4.896× 10^4 hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
z_{shale} = 91.44m

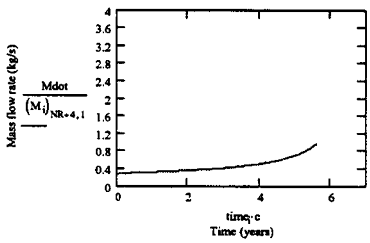


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.54\times 10^4 \\ 3.531\times 10^4 \end{pmatrix}$$

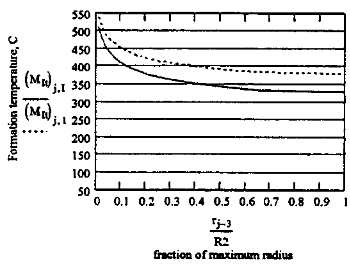
i := 1.. Npts

$$c := \frac{1}{3.15 \cdot 10^7}$$

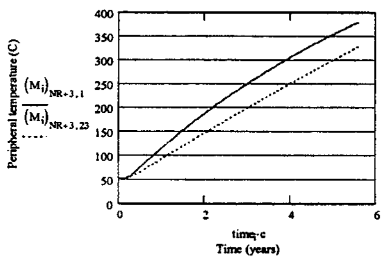


l := 23 **(# steps above well bottom)** j := 3.. NR + 3

tmax = 4.896× 10^4 hr Nt = 6.12× 10^3 Nsfrq = 10 Npts = 612 It = 612



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 12.491 psi$ $\quad \Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[(M_{It})_{0,i} - (M_{It})_{1,i} \right]$ $\quad \Delta Pg = 14.835 psi$

$\Delta P_1 \cdot Pa = 13.011 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $\quad P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $\quad P_{pump} = 154.733 watt$

$\Delta ptotal = 40.337 psi$

salt volume per well

$V_{salt} := (Axu_1 + Axd_1) \cdot z_{shale} + (Axu_0 + Axd_0) \cdot z_{overburden}$

mass per well if salt is at 270 C

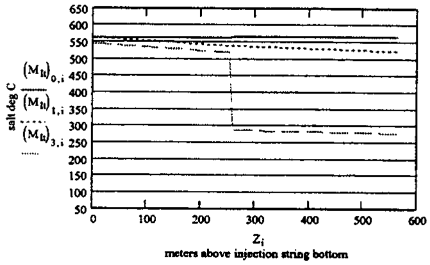
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $\quad M_{salt} = 4.428 \times 10^3 lb$ $\quad$ **20 wells:** $M_{salt} \cdot 20 = 8.856 \times 10^4 lb$

******************** **END MOLTEN SALT CASE 8** ***********************

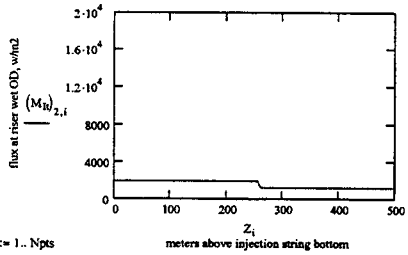
******************** START MOLTEN SALT CASE 9 ********************

PLOTS $tmax = 3.312 \times 10^4 hr$ $Nt = 4.14 \times 10^3$ $Nsfrq = 10$ $Npts = 414$ $It = 414$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 3.312 \times 10^4 hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08m$

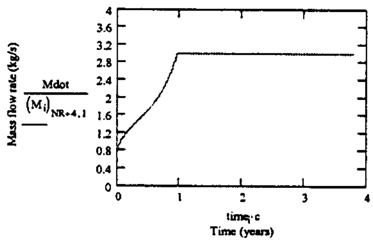


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 8.405 \times 10^4 \\ 1.136 \times 10^5 \end{pmatrix}$$

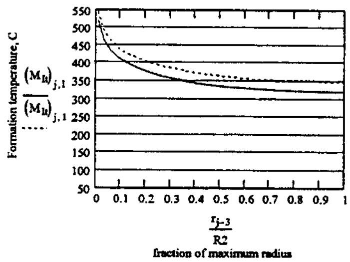
$i := 1..Npts$

$$c := \frac{1}{3.15 \cdot 10^7}$$

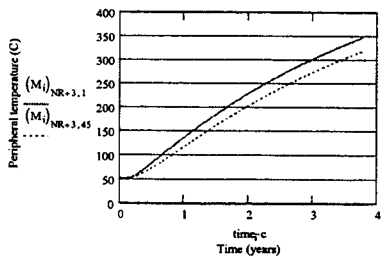


$I := 45$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 3.312 \times 10^4 hr$ $Nt = 4.14 \times 10^3$ $Nsfrq = 10$ $Npts = 414$ $It = 414$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 151.857 psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 12.278 psi$

$\Delta P_1 \cdot Pa = 148.524 psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 3.751 \times 10^3 \, watt$

$\Delta ptotal = 312.659 psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

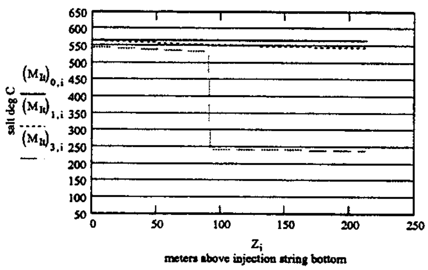
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $\quad M_{salt} = 6.302 \times 10^3 \, lb$ $\quad$ **20 wells:** $M_{salt} \cdot 20 = 1.26 \times 10^5 \, lb$

******************** **END MOLTEN SALT CASE 9** **********************

******************* START MOLTEN SALT CASE 10 *******************

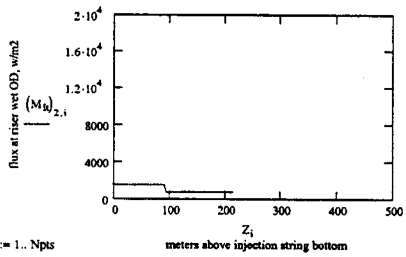
PLOTS tmax = 5.04 × 10³ hr Nt = 630 Nsfrq = 10 Npts = 63 It = 63 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 5.04 × 10³ hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing

$z_{shale} = 91.44$m

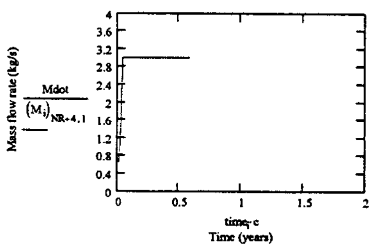


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 4.323 \times 10^4 \\ 6.222 \times 10^4 \end{pmatrix}$$

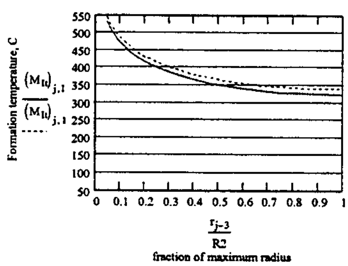
i := 1.. Npts

$$c := \frac{1}{3.15 \cdot 10^7}$$

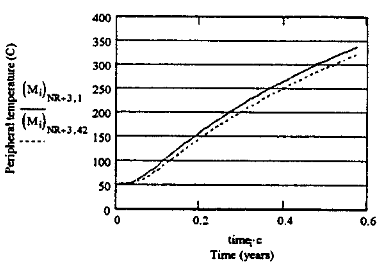


I := 42 **(# steps above well bottom)** j := 3.. NR + 3

tmax = 5.04 × 10³ hr Nt = 630 Nsfrq = 10 Npts = 63 It = 63



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 1.79psi$ $\quad$ $\Delta Pg := 6.06\frac{newton}{m^3}\cdot\Delta z\cdot\sum_{i=1}^{NW}\left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i}\right]$ $\quad$ $\Delta Pg = 2.$

$\Delta P_1 \cdot Pa = 1.818psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $\quad$ $P_{pump} := \frac{Mdot}{\rho_{salt}\cdot Mf}\cdot\Delta ptotal$ $\quad$ $P_{pump} = 73.835watt$

$\Delta ptotal = 6.154psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right)\cdot z_{shale} + \left(Axu_0 + Axd_0\right)\cdot z_{overburden}$

mass per well if salt is at 270 C

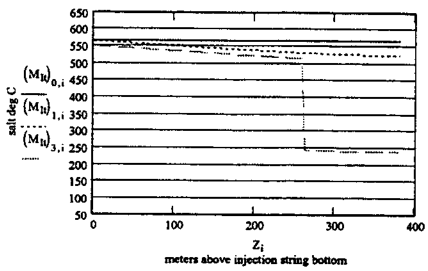
$M_{salt} := V_{salt}\cdot 1918\frac{kg}{m^3}$ $\quad$ $M_{salt} = 9.538\times 10^3\,lb$ $\quad$ **20 wells:** $M_{salt}\cdot 20 = 1.908\times 10^5\,lb$

******************** **END MOLTEN SALT CASE 10** **********************

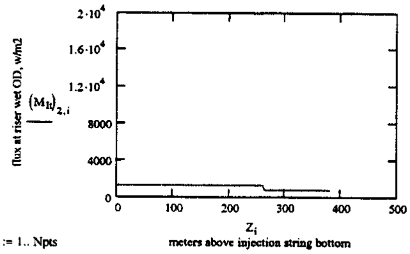
******************* START MOLTEN SALT CASE 11 *******************

PLOTS $tmax = 5.76\times10^3$ hr Nt = 720 Nsfrq = 10 Npts = 72 It = 72 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 5.76×10^3 hr



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08$m

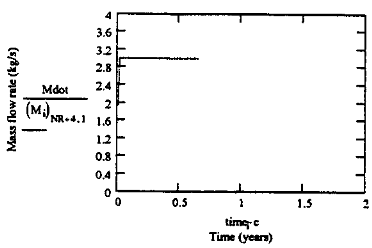


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 4.034\times10^4 \\ 1.587\times10^5 \end{pmatrix}$$

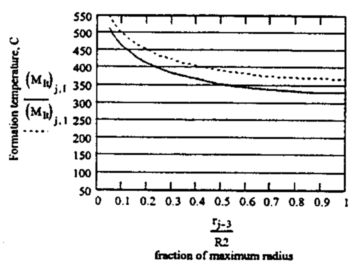
i := 1.. Npts

$$c := \frac{1}{3.15\cdot10^7}$$

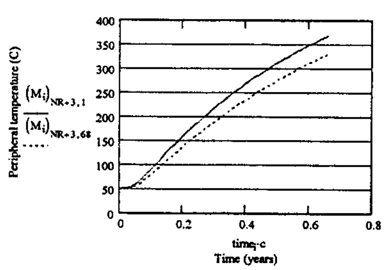


I := 68 **(# steps above well bottom)** j := 3.. NR + 3

$tmax = 5.76\times10^3$ hr Nt = 720 Nsfrq = 10 Npts = 72 It = 72



i := 1.. Npts



$|\Delta P$

$\Delta P_0 \cdot Pa = 3.198psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It} \right)_{0,i} - \left(M_{It} \right)_{1,i} \right]$

$\Delta Pg = 8.364psi$

$\Delta P_1 \cdot Pa = 3.264psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 177.868watt$

$\Delta ptotal = 14.825psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1 \right) \cdot z_{shale} + \left(Axu_0 + Axd_0 \right) \cdot z_{overburden}$

mass per well if salt is at 270 C

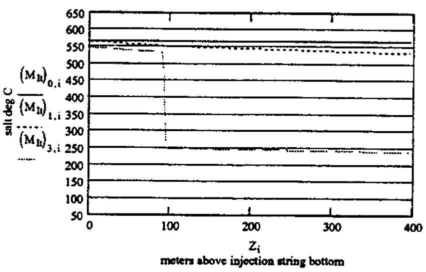
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 1.703 \times 10^4 lb$ **20 wells:** $M_{salt} \cdot 20 = 3.406 \times 10^5 lb$

******************** **END MOLTEN SALT CASE 11** **********************

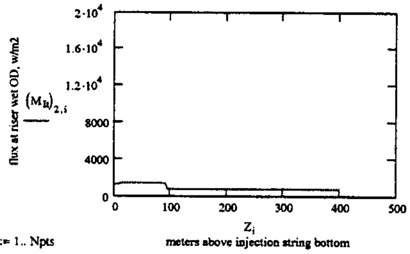
******************** START MOLTEN SALT CASE 12 ******************

PLOTS $tmax = 5.76\times 10^3 hr$ $Nt = 720$ $Nsfrq = 10$ $Npts = 72$ $It = 72$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 5.76\times 10^3 hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 91.44m$

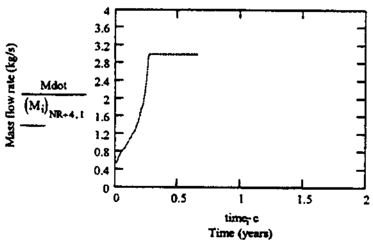


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 1.03\times 10^5 \\ 5.797\times 10^4 \end{pmatrix}$$

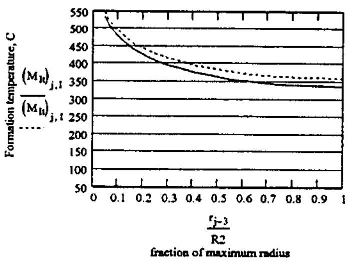
$i := 1..Npts$

$$c := \frac{1}{3.15\cdot 10^7}$$

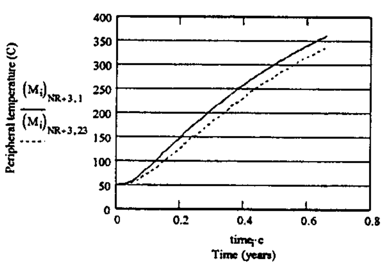


$I := 23$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 5.76\times 10^3 hr$ $Nt = 720$ $Nsfrq = 10$ $Npts = 72$ $It = 72$



$i := 1..Npts$



ΔP

$\Delta P_0 \cdot Pa = 3.325psi$ $\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$ $\Delta Pg = 7.($

$\Delta P_1 \cdot Pa = 3.387psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $P_{pump} = 164.687watt$

$\Delta ptotal = 13.726psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

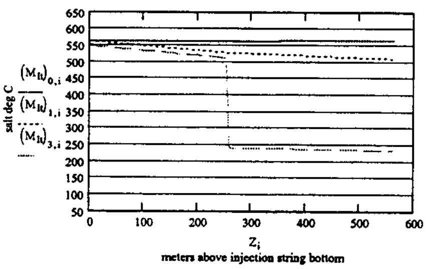
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 1.771 \times 10^4 lb$ **20 wells:** $M_{salt} \cdot 20 = 3.543 \times 10^5 lb$

******************** **END MOLTEN SALT CASE 12** *********************

******************** START MOLTEN SALT CASE 13 ******************

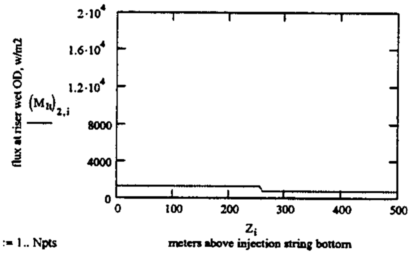
PLOTS $tmax = 5.76\times 10^{3}\,hr$ $Nt = 720$ $Nsfrq = 10$ $Npts = 72$ $It = 72$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 5.76\times 10^{3}\,hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing

$z_{shale} = 259.08m$

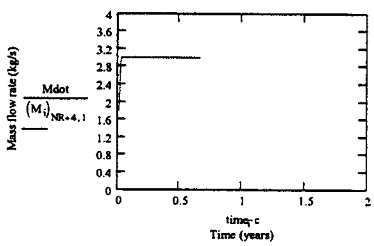


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 9.99\times 10^{4} \\ 1.554\times 10^{5} \end{pmatrix}$$

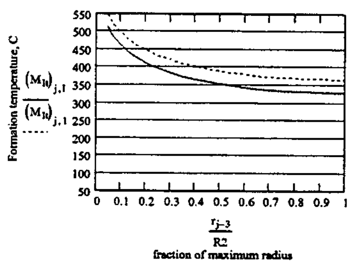
$i := 1..Npts$

$$c := \frac{1}{3.15\cdot 10^{7}}$$

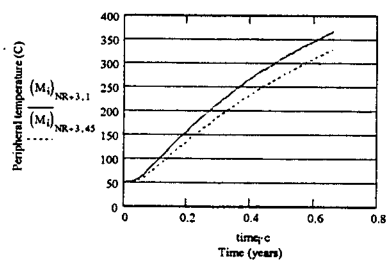


$I := 45$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 5.76\times 10^{3}\,hr$ $Nt = 720$ $Nsfrq = 10$ $Npts = 72$ $It = 72$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 4.735psi$

$\Delta Pg := 6.06\frac{newton}{m^3}\cdot\Delta z\cdot\sum_{i=1}^{NW}\left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i}\right]$

$\Delta Pg = 16.618psi$

$\Delta P_1 \cdot Pa = 4.85psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt}\cdot Mf}\cdot\Delta ptotal$

$P_{pump} = 314.385watt$

$\Delta ptotal = 26.203psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right)\cdot z_{shale} + \left(Axu_0 + Axd_0\right)\cdot z_{overburden}$

mass per well if salt is at 270 C

$M_{salt} := V_{salt}\cdot 1918\frac{kg}{m^3}$

$M_{salt} = 2.521\times 10^4 lb$

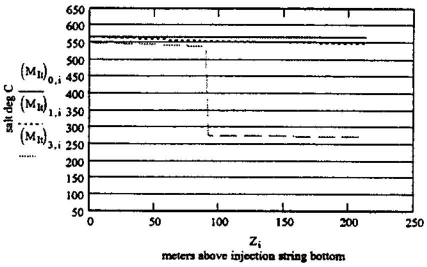
20 wells: $M_{salt}\cdot 20 = 5.041\times 10^5 lb$

******************** **END MOLTEN SALT CASE 13** **********************

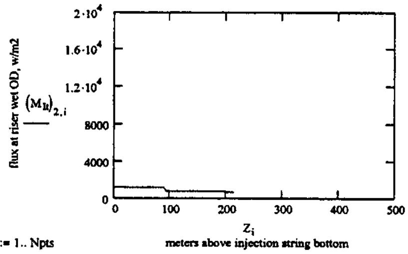
******************** START MOLTEN SALT CASE 14 ******************

PLOTS $tmax = 2.52 \times 10^4\,hr$ $Nt = 3.15 \times 10^3$ $Nsfrq = 10$ $Npts = 315$ $It = 315$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 2.52 \times 10^4\,hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 91.44m$

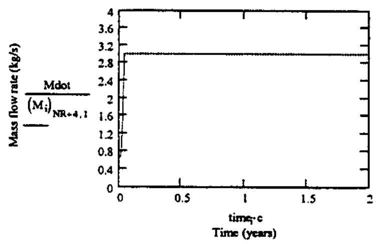


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.93 \times 10^4 \\ 5.025 \times 10^4 \end{pmatrix}$$

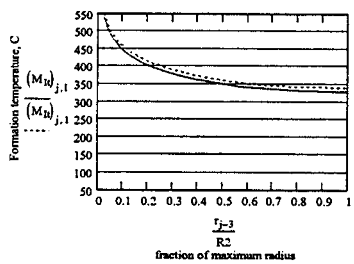
$i := 1..Npts$

$$c := \frac{1}{3.15 \cdot 10^7}$$

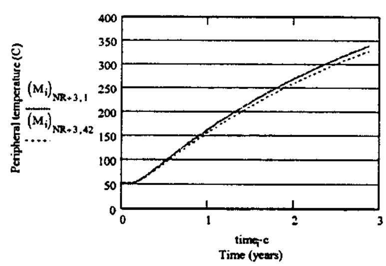


$I := 42$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 2.52 \times 10^4\,hr$ $Nt = 3.15 \times 10^3$ $Nsfrq = 10$ $Npts = 315$ $It = 315$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 1.79psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 2.111psi$

$\Delta P_1 \cdot Pa = 1.815psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 68.581watt$

$\Delta ptotal = 5.716psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$

$M_{salt} = 9.538 \times 10^3 \, lb$

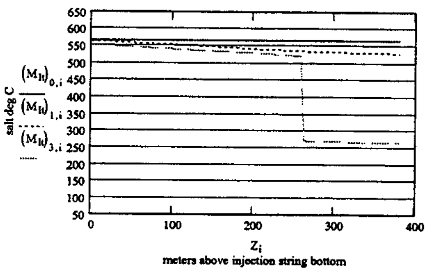
20 wells: $M_{salt} \cdot 20 = 1.908 \times 10^5 \, lb$

******************** **END MOLTEN SALT CASE 14** **********************

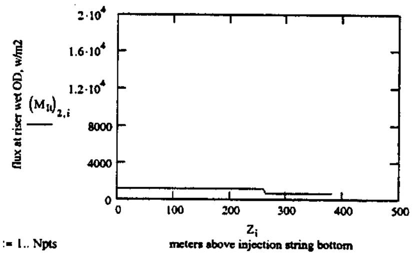
******************** START MOLTEN SALT CASE 15 ********************

PLOTS $tmax = 2.664 \times 10^4 hr$ $Nt = 3.33 \times 10^3$ $Nsfrq = 10$ $Npts = 333$ $It = 333$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 2.664 \times 10^4 hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08m$

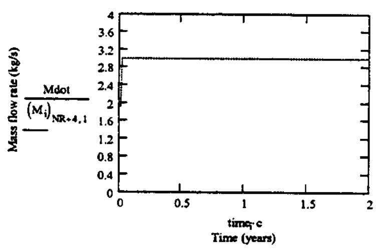


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 3.739 \times 10^4 \\ 1.379 \times 10^5 \end{pmatrix}$$

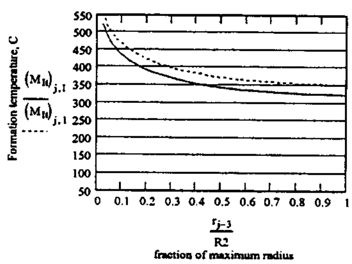
$i := 1..Npts$

$$c := \frac{1}{3.15 \cdot 10^7}$$

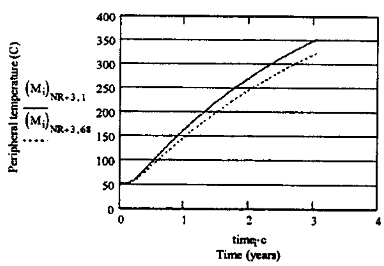


$I := 68$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 2.664 \times 10^4 hr$ $Nt = 3.33 \times 10^3$ $Nsfrq = 10$ $Npts = 333$ $It = 333$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 3.198psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 7.311psi$

$\Delta P_1 \cdot Pa = 3.259psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 165.177watt$

$\Delta ptotal = 13.767psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

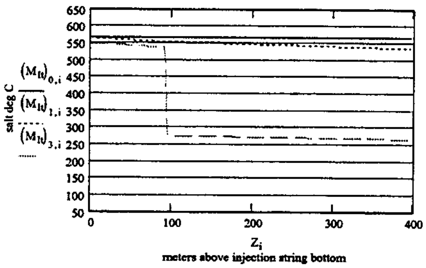
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 1.703 \times 10^4 lb$ **20 wells:** $M_{salt} \cdot 20 = 3.406 \times 10^5 lb$

******************** **END MOLTEN SALT CASE 15** *********************

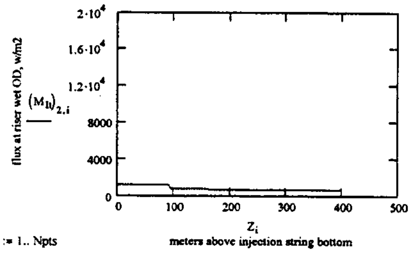
******************** START MOLTEN SALT CASE 16 ********************

PLOTS $tmax = 2.592\times 10^{4}\,hr$ $Nt = 3.24\times 10^{3}$ $Nsfrq = 10$ $Npts = 324$ $It = 324$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 2.592\times 10^{4}\,hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 91.44m$

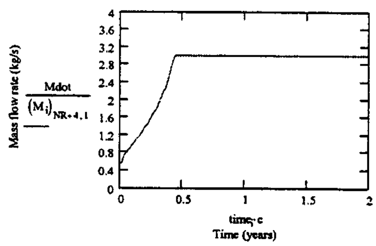


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 9.503\times 10^{4} \\ 5.023\times 10^{4} \end{pmatrix}$$

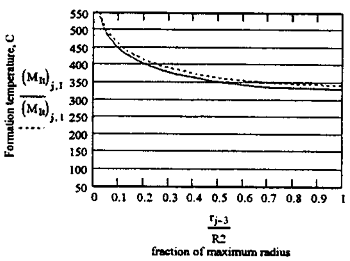
$i := 1..Npts$

$$c := \frac{1}{3.15\cdot 10^{7}}$$

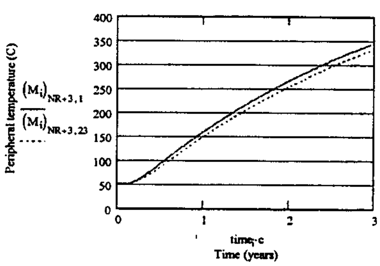


$I := 23$ **(# steps above well bottom)** $j := 3..NR + 3$

$tmax = 2.592\times 10^{4}\,hr$ $Nt = 3.24\times 10^{3}$ $Nsfrq = 10$ $Npts = 324$ $It = 324$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 3.325psi$

$\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$

$\Delta Pg = 6.249psi$

$\Delta P_1 \cdot Pa = 3.383psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$

$P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$

$P_{pump} = 155.457watt$

$\Delta ptotal = 12.957psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

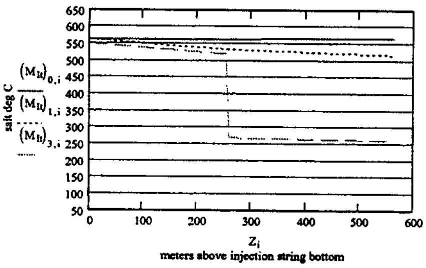
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $M_{salt} = 1.771 \times 10^4 lb$ **20 wells:** $M_{salt} \cdot 20 = 3.543 \times 10^5 lb$

******************** **END MOLTEN SALT CASE 16** *********************

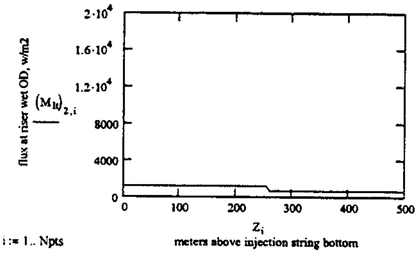
******************** START MOLTEN SALT CASE 17 ********************

PLOTS $tmax = 2.664\times 10^{4}\,hr$ $Nt = 3.33\times 10^{3}$ $Nsfrq = 10$ $Npts = 333$ $It = 333$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 2.664\times 10^{4}\,hr$



0 : inner salt
1 : outer salt
2 : flux to well bore
3 : casing
$z_{shale} = 259.08\,m$

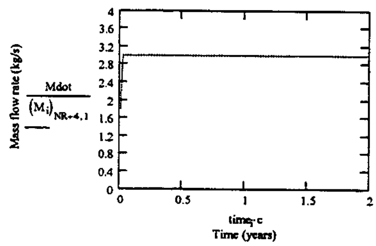


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 9.291\times 10^{4} \\ 1.349\times 10^{5} \end{pmatrix}$$

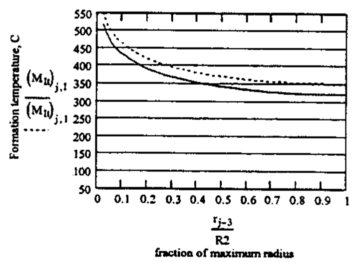
$i := 1..Npts$

$$c := \frac{1}{3.15\cdot 10^{7}}$$

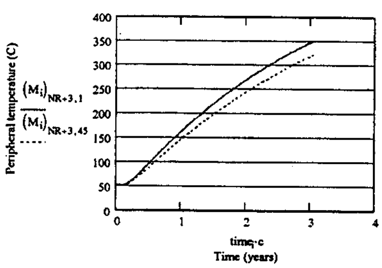


$I := 45$ **(# steps above well bottom)** $j := 3..NR+3$

$tmax = 2.664\times 10^{4}\,hr$ $Nt = 3.33\times 10^{3}$ $Nsfrq = 10$ $Npts = 333$ $It = 333$



$i := 1..Npts$



$|\Delta P$

$\Delta P_0 \cdot Pa = 4.734psi$ $\quad$ $\Delta Pg := 6.06 \frac{newton}{m^3} \cdot \Delta z \cdot \sum_{i=1}^{NW} \left[\left(M_{It}\right)_{0,i} - \left(M_{It}\right)_{1,i} \right]$ $\quad$ $\Delta Pg = 14.63psi$

$\Delta P_1 \cdot Pa = 4.842psi$

$\Delta ptotal := \Delta P_0 \cdot Pa + \Delta P_1 \cdot Pa + \Delta Pg$ $\quad$ $P_{pump} := \frac{Mdot}{\rho_{salt} \cdot Mf} \cdot \Delta ptotal$ $\quad$ $P_{pump} = 290.423watt$

$\Delta ptotal = 24.206psi$

salt volume per well

$V_{salt} := \left(Axu_1 + Axd_1\right) \cdot z_{shale} + \left(Axu_0 + Axd_0\right) \cdot z_{overburden}$

mass per well if salt is at 270 C

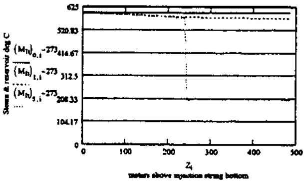
$M_{salt} := V_{salt} \cdot 1918 \frac{kg}{m^3}$ $\quad$ $M_{salt} = 2.521 \times 10^4 \, lb$ $\quad$ **20 wells:** $M_{salt} \cdot 20 = 5.041 \times 10^5 \, lb$

******************** **END MOLTEN SALT CASE 17** **********************

APPENDIX H: STEAM PARAMETRIC STUDY

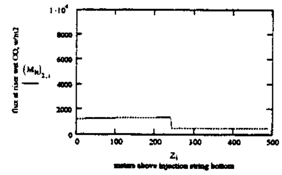
******************** START STEAM CASE 1 ***************************

PLOTS $tmax = 1.584\times 10^{4}\,hr$ $Nt = 1.98\times 10^{3}$ $Nsfrq = 10$ $Npts = 198$ $lt = 198$ $i := 0..NW$



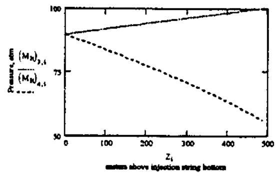
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 243.84m$

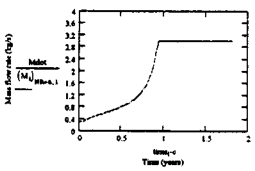


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 5.461\times 10^{4} \\ 1.467\times 10^{5} \end{pmatrix}$$

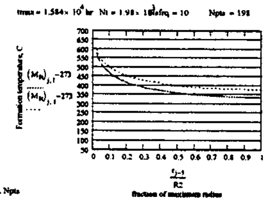


$i := 1..Npts$

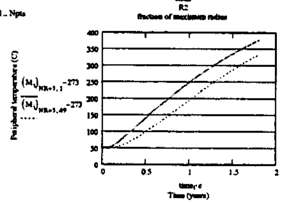


$l := 49$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 1.584\times 10^{4}\,hr$ $Nt = 1.98\times 10^{3}$ $Nsfrq = 10$ $Npts = 198$ $lt = 198$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $lt = 198$

$$Ein := MdotCp\cdot Nsfrq\cdot \Delta t\cdot \sum_{i=1}^{lt-1}\left[\frac{Ts - \dfrac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$ **Based on steam ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{lt})_{NR+6,1}}\cdot Nsfrq\cdot \Delta t\left[Ts - \left[1.5(M_{lt})_{1,NW} - 0.5(M_{lt-1})_{1,NW}\right]\cdot K\right]\right]$$

$Ein = 1.54\times 10^{13}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval lt-1 to lt

---

$$\Delta ER := CR\rho\cdot \Delta z\cdot \pi\cdot \sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot \sum_{i=0}^{NW}\left[\frac{(M_{lt})_{j+5,i} + (M_{lt})_{j+6,i}}{2}\cdot K - Tw_i\right]$$ **Based on reservoir ΔTs**

$\Delta ER = 1.447\times 10^{13}\,joule$ $\quad \dfrac{\Delta ER}{Ein} - 1 = -0.06$

$$Ew := \left| \begin{array}{l} Q_0 \leftarrow 0 \\ Q_1 \leftarrow 0 \\ \text{for } l \in 1..lt \\ \quad \left| \begin{array}{l} i \leftarrow 1 \\ \text{while } i \le NW \\ \quad \left| \begin{array}{l} j \leftarrow if(i > NW1, 0, 1) \\ Q_j \leftarrow \left[\dfrac{(M_l)_{(2,i-1)} + (M_l)_{(2,i)}}{2}\right]\cdot \dfrac{AdZ_j}{m^2} + Q_j \\ i \leftarrow i + 1 \end{array}\right. \end{array}\right. \\ Q \end{array}\right.$$

Based on riser OD flux

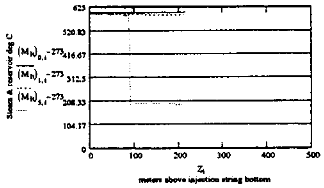
$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t = 1.556\times 10^{13}\,joule$

$\dfrac{Ew_0}{Ew_0 + Ew_1} = 0.181$ **overburden fraction**

$\dfrac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t}{Ein} - 1 = 0.01$

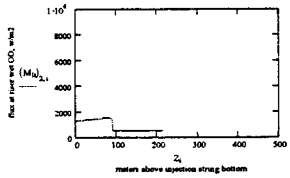
******************** START STEAM CASE 2 ****************************

PLOTS $tmax = 6.48 \times 10^{3}\,hr$ $Nt = 810$ $Nsfrq = 10$ $Npts = 81$ $It = 81$ $s := 0..NW$



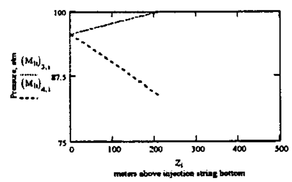
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
6+ : formation

$z_{shale} = 91.44m$

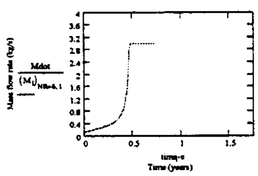


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 2.944 \times 10^{4} \\ 6.045 \times 10^{4} \end{pmatrix}$$

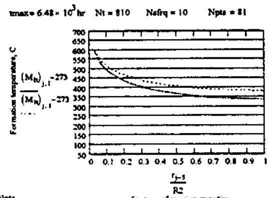


$i := 1..Npts$

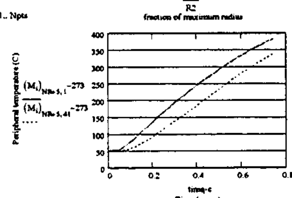


$l := 41$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 6.48 \times 10^{3}\,hr$ $Nt = 810$ $Nsfrq = 10$ $Npts = 81$ $It = 81$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 81$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$ **Based on steam ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{1,NW} - 0.5 (M_{It-1})_{1,NW} \right] \cdot K \right] \right]$$

$Ein = 2.665 \times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CR\rho \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$ **Based on reservoir ΔTs**

$\Delta ER = 2.536 \times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.049$

```
Ew := | Q0 ← 0
      | Q1 ← 0
      | for l ∈ 1..It
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NWI, 0, 1)
      |   |   | Qj ← [((Ml)(2,i-1) + (Ml)(2,i)) / 2] · AdZj / m^2 + Qj
      |   |   | i ← i + 1
      | Q
```

Based on riser OD flux

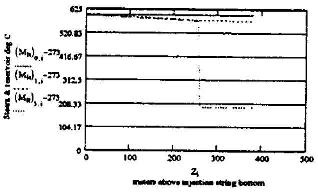
$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 2.732 \times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.217$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = 0.025$

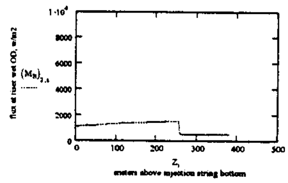
******************** START STEAM CASE 3 *****************************

PLOTS $tmax = 7.92 \times 10^3 hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$ $i := 0..NW$



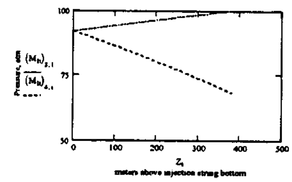
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 259.08m$

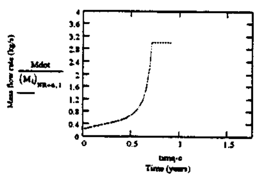


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 2.817 \times 10^4 \\ 1.642 \times 10^5 \end{pmatrix}$$

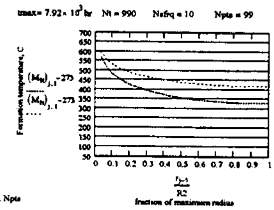


$i := 1..Npts$

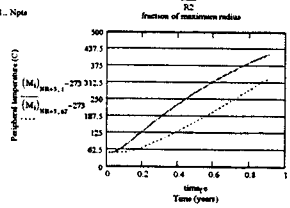


$I := 67$ **(# steps above well bottom)** $j := 5..NR + 5$

$tmax = 7.92 \times 10^3 hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 99$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on steam ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \left[Ts - \left[1.5 (M_{It})_{1,NW} - 0.5 (M_{It-1})_{1,NW} \right] \cdot K \right] \right]$$

$$Ein = 7.088 \times 10^{12} joule$$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CR\rho \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_j \right]$$

Based on reservoir ΔTs

$\Delta ER = 6.371 \times 10^{12} joule$ $\frac{\Delta ER}{Ein} - 1 = -0.101$

$$Ew := \left| \begin{array}{l} Q_0 \leftarrow 0 \\ Q_1 \leftarrow 0 \\ \text{for } I \in 1..It \\ \quad \left| \begin{array}{l} i \leftarrow 1 \\ \text{while } i \le NW \\ \quad \left| \begin{array}{l} j \leftarrow if(i > NW1, 0, 1) \\ Q_j \leftarrow \left[\frac{(M_I)_{(2,i-1)} + (M_I)_{(2,i)}}{2} \right] \cdot \frac{AdZ_j}{m^2} + Q_j \\ i \leftarrow i + 1 \end{array} \right. \end{array} \right. \\ Q \end{array} \right.$$

Based on riser OD flux

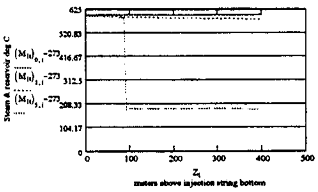
$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 7.209 \times 10^{12} joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.081$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = 0.017$

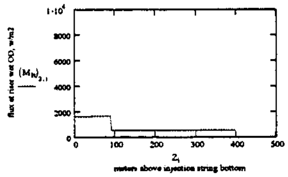
******************** START STEAM CASE 4 ***************************

PLOTS $tmax = 5.04\times 10^{3}\,hr$ $Nt = 630$ $Nsfrq = 10$ $Npts = 63$ $It = 63$ $i := 0..NW$



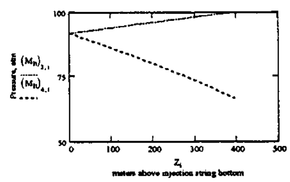
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

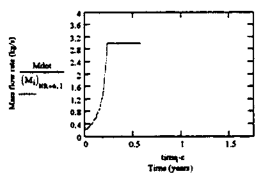


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.344\times 10^{4} \\ 7.123\times 10^{4} \end{pmatrix}$$

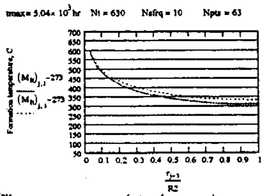


$i := 1..Npts$

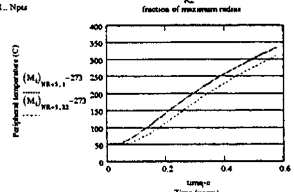


$I := 22$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 5.04\times 10^{3}\,hr$ $Nt = 630$ $Nsfrq = 10$ $Npts = 63$ $It = 63$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 63$

$$Ein := MdotCp\cdot Nsfrq\cdot\Delta t\cdot\sum_{i=1}^{It-1}\left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$

Based on steam ΔT and MdotCp:

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot\Delta t\cdot\left[Ts - \left[1.5(M_{It})_{1,NW} - 0.5(M_{It-1})_{1,NW}\right]\cdot K\right]\right]$$

$$Ein = 3.171\times 10^{12}\,joule$$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\cdot\Delta z\cdot\pi\cdot\sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot\sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2}\cdot K - Tw_i\right]$$

Based on reservoir ΔTs

$$\Delta ER = 3.017\times 10^{12}\,joule \qquad \frac{\Delta ER}{Ein} - 1 = -0.048$$

```
Ew := | Q_0 ← 0
      | Q_1 ← 0
      | for l ∈ 1..It
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NW1, 0, 1)
      |   |   | Q_j ← [((M_l)_(2,i-1) + (M_l)_(2,i)) / 2] · AdZ_i / m^2 + Q_j
      |   |   | i ← i + 1
      | Q
```

Based on riser OD flux

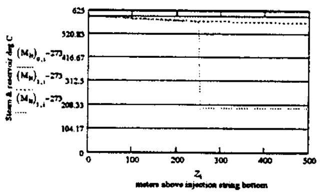
$$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot\Delta t = 3.26\times 10^{12}\,joule$$

$$\frac{Ew_0}{Ew_0 + Ew_1} = 0.387$$ **overburden fraction**

$$\frac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot\Delta t}{Ein} - 1 = 0.028$$

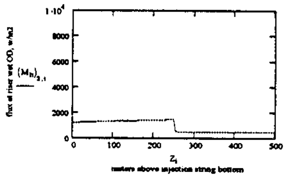
******************** START STEAM CASE 5 ****************************

PLOTS $tmax = 7.2 \times 10^{3}\,hr$ $Nt = 900$ $Nafrq = 10$ $Npts = 90$ $It = 90$ $i := 0..NW$



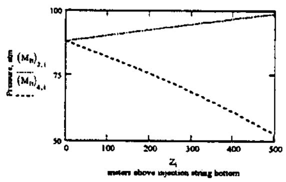
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 259.08\,m$

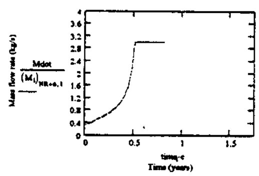


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.094 \times 10^{4} \\ 1.598 \times 10^{5} \end{pmatrix}$$

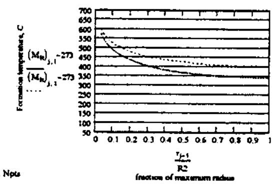


$i := 1..Npts$

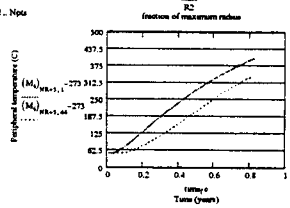


$I := 44$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 7.2 \times 10^{3}\,hr$ $Nt = 900$ $Nafrq = 10$ $Npts = 90$ $It = 90$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 90$

$$Ein := MdotCp \cdot Nafrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on steam ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nafrq \cdot \Delta t \left\{ Ts - \left[1.5 (M_{It})_{1,NW} - 0.5 (M_{It-1})_{1,NW} \right] \cdot K \right\} \right]$$

$Ein = 7.971 \times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 7.197 \times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.097$

$$Ew := \left| \begin{array}{l} Q_0 \leftarrow 0 \\ Q_1 \leftarrow 0 \\ \text{for } I \in 1..It \\ \quad \left| \begin{array}{l} i \leftarrow 1 \\ \text{while } i \le NW \\ \quad \left| \begin{array}{l} j \leftarrow if(i > NWI, 0, 1) \\ Q_j \leftarrow \left[\frac{(M_I)_{(2,i-1)} + (M_I)_{(2,i)}}{2} \right] \cdot \frac{AdZ_i}{m^2} + Q_j \\ i \leftarrow i + 1 \end{array} \right. \end{array} \right. \\ Q \end{array} \right.$$

Based on riser OD flux

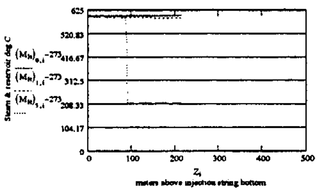
$(Ew_0 + Ew_1) \cdot watt \cdot Nafrq \cdot \Delta t = 8.105 \times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.188$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nafrq \cdot \Delta t}{Ein} - 1 = 0.017$

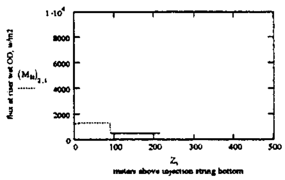
******************** START STEAM CASE 6 ****************************

PLOTS $tmax = 2.592\times10^{4}\,hr$ $Nt = 3.24\times10^{3}$ $Nsfrq = 10$ $Npts = 324$ $It = 324$ $i := 0..NW$



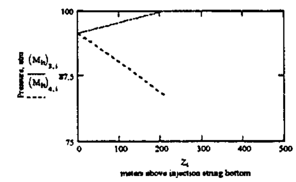
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

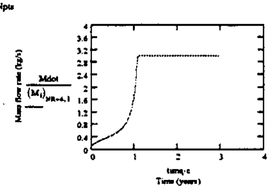


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 2.807\times10^{4} \\ 5.467\times10^{4} \end{pmatrix}$$

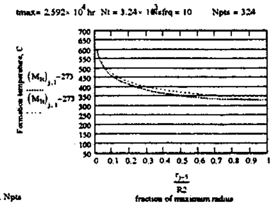


$\iota := 1..Npts$

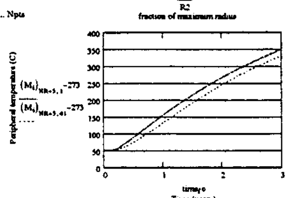


$I := 41$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 2.592\times10^{4}\,hr$ $Nt = 3.24\times10^{3}$ $Nsfrq = 10$ $Npts = 324$ $It = 324$



$\iota := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 324$

$$Ein := MdotCp\cdot Nsfrq\cdot\Delta t\cdot\sum_{\iota=1}^{It-1}\left[\frac{Ts-\dfrac{(M_\iota)_{1,NW}+(M_{\iota+1})_{1,NW}}{2}\cdot K}{(M_\iota)_{NR+6,1}}\right]$$

Based on steam ΔT and MdotCp;

$$Ein := Ein+\left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot\Delta t\cdot\left[Ts-\left[1.5(M_{It})_{1,NW}-0.5(M_{It-1})_{1,NW}\right]\cdot K\right]\right]$$

$Ein = 1.016\times10^{13}\,joule$

"Ein" sum based on fact that temp at ι=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\cdot\Delta z\cdot\pi\cdot\sum_{j=0}^{NR-1}\left[(r_{j+1})^2-(r_j)^2\right]\cdot\sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i}+(M_{It})_{j+6,i}}{2}\cdot K-Tw_i\right]$$

Based on reservoir ΔTs

$\Delta ER = 9.791\times10^{12}\,joule$ $\dfrac{\Delta ER}{Ein}-1 = -0.036$

```
Ew := | Q0 ← 0
      | Q1 ← 0
      | for I ∈ 1..It
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NW1, 0, 1)
      |   |   | Qj ← [((M_I)(2,i-1) + (M_I)(2,i)) / 2] · AdZ_j / m^2 + Qj
      |   |   | i ← i + 1
      | Q
```

Based on riser OD flux

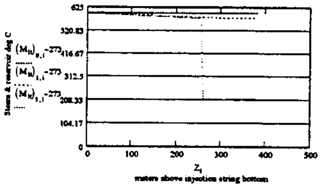
$(Ew_0+Ew_1)\cdot watt\cdot Nsfrq\cdot\Delta t = 1.026\times10^{13}\,joule$

$\dfrac{Ew_0}{Ew_0+Ew_1} = 0.254$ **overburden fraction**

$\dfrac{(Ew_0+Ew_1)\cdot watt\cdot Nsfrq\cdot\Delta t}{Ein}-1 = 0.01$

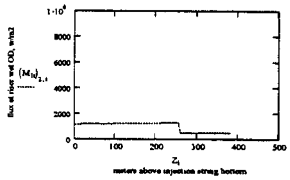
******************** START STEAM CASE 7 ****************************

PLOTS $tmax = 2.952 \times 10^4\,hr$ $Nt = 3.69 \times 10^3$ $Nsfrq = 10$ $Npts = 369$ $It = 369$ $i := 0..NW$



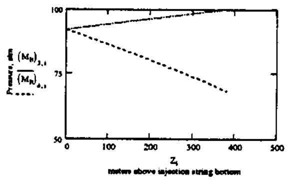
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 259.08m$

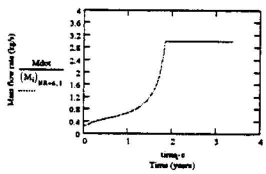


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 2.692 \times 10^4 \\ 1.497 \times 10^5 \end{pmatrix}$$

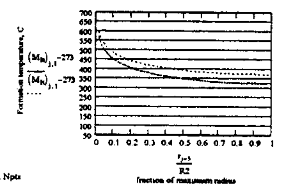


$i := 1..Npts$

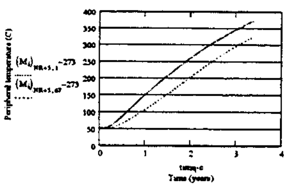


$I := 67$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 2.952 \times 10^4\,hr$ $Nt = 3.69 \times 10^3$ $Nsfrq = 10$ $Npts = 369$ $It = 369$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 369$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on steam ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left\{ Ts - \left[1.5 \cdot (M_{It})_{1,NW} - 0.5 \cdot (M_{It-1})_{1,NW} \right] \cdot K \right\} \right]$$

$Ein = 2.541 \times 10^{13}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 2.403 \times 10^{13}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.054$

```
Ew := | Q0 ← 0
      | Q1 ← 0
      | for I ∈ 1..It
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NW1, 0, 1)
      |   |   | Qj ← [((MI)(2,i-1) + (MI)(2,i)) / 2] · (AdZi / m^2) + Qj
      |   |   | i ← i + 1
      | Q
```

Based on riser OD flux

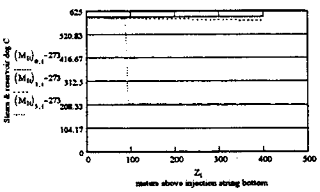
$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 2.56 \times 10^{13}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.1$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = 7.51 \times 10^{-3}$

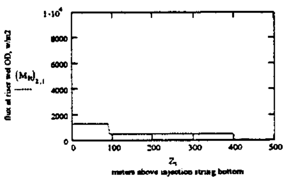
******************** START STEAM CASE 8 ****************************

PLOTS $tmax = 2.448 \times 10^4\,hr$ $Nt = 3.06 \times 10^3$ $Nsfrq = 10$ $Npts = 306$ $It = 306$ $i := 0..NW$



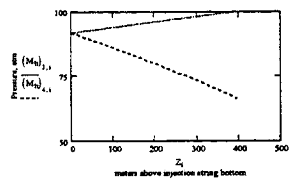
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

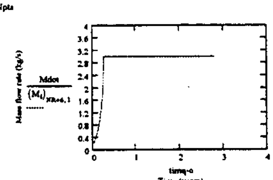


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 6.89 \times 10^4 \\ 5.666 \times 10^4 \end{pmatrix}$$

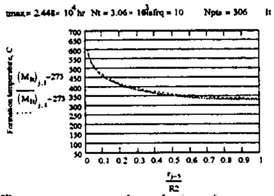


$i := 1..Npts$

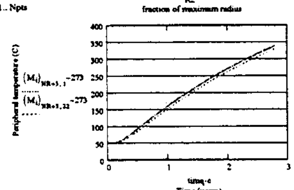


$I := 22$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 2.448 \times 10^4\,hr$ $Nt = 3.06 \times 10^3$ $Nsfrq = 10$ $Npts = 306$ $It = 306$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 306$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on steam ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{1,NW} - 0.5 (M_{It-1})_{1,NW} \right] \cdot K \right] \right]$$

$Ein = 1.392 \times 10^{13}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CR\rho \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 1.346 \times 10^{13}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.033$

```
Ew := | Q0 ← 0
      | Q1 ← 0
      | for I ∈ 1..It
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NW1, 0, 1)
      |   |   | Qj ← [ ((M_I)(2,i-1) + (M_I)(2,i)) / 2 ] · AdZ_i / m^2 + Qj
      |   |   | i ← i + 1
      | Q
```

Based on riser OD flux

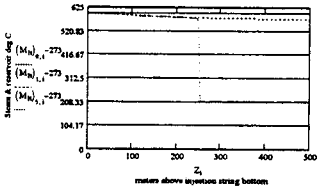
$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 1.405 \times 10^{13}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.453$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = 9.231 \times 10^{-3}$

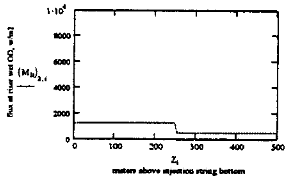
******************** START STEAM CASE 9 ****************************

PLOTS tmax = $2.736 \cdot 10^4$ hr Nt = $3.42 \cdot 10^3$ Nsfrq = 10 Npts = 342 lt = 342 i := 0.. NW



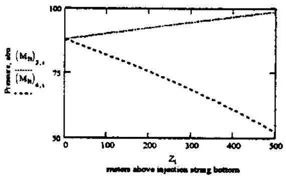
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

z_{shale} = 259.08m

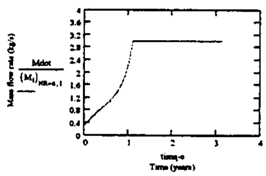


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 6.801 \times 10^4 \\ 1.486 \times 10^5 \end{pmatrix}$$

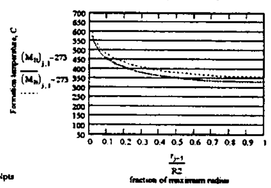


i := 1.. Npts

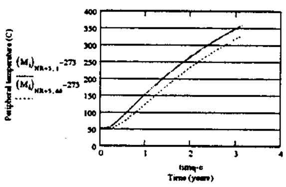


I := 44 (# steps above well bottom) j := 5.. NR + 5

tmax = $2.736 \cdot 10^4$ hr Nt = $3.42 \cdot 10^3$ Nsfrq = 10 Npts = 342 lt = 342



i := 1.. Npts



SYSTEM ENERGY BALANCE APPROXIMATE CHECK lt = 342

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{lt-1} \left[\frac{Ts - \frac{(M_i)_{1,NW} + (M_{i+1})_{1,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on steam ΔT and MdotCp:

$$Ein := Ein + \left[\frac{MdotCp}{(M_{lt})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{lt})_{1,NW} - 0.5 (M_{lt-1})_{1,NW} \right] \cdot K \right] \right]$$

$Ein = 2.876 \times 10^{13}$ joule

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval lt-1 to lt

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{lt})_{j+5,i} + (M_{lt})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 2.722 \cdot 10^{13}$ joule $\frac{\Delta ER}{Ein} - 1 = -0.053$

```
Ew := | Q0 ← 0
      | Q1 ← 0
      | for l ∈ 1.. lt
      |   | i ← 1
      |   | while i ≤ NW
      |   |   | j ← if(i > NW1, 0, 1)
      |   |   | Qj ← [((Ml)(2,i-1) + (Ml)(2,i)) / 2] · AdZi / m^2 + Qj
      |   |   | i ← i + 1
      | Q
```

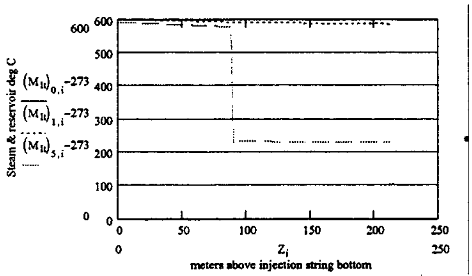
Based on riser OD flux

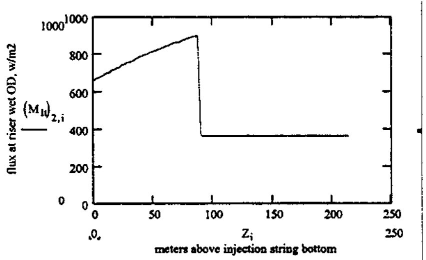
$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 2.891 \times 10^{13}$ joule

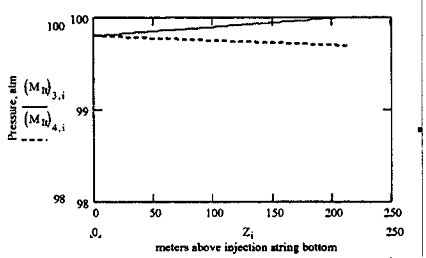
$\frac{Ew_0}{Ew_0 + Ew_1} = 0.226$ **overburden fraction**

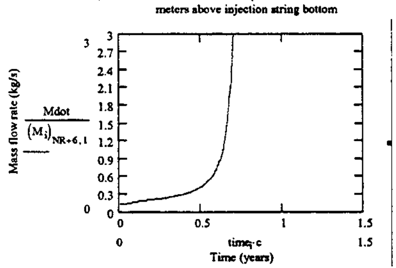
$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = 5.093 \cdot 10^{-3}$

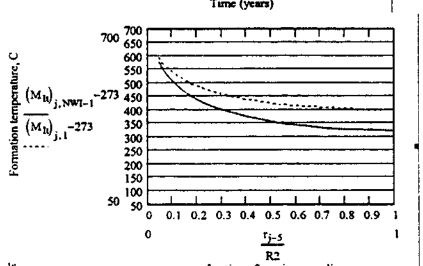
******************** START STEAM CASE 10 ****************************

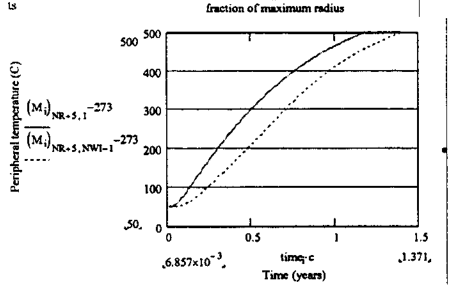




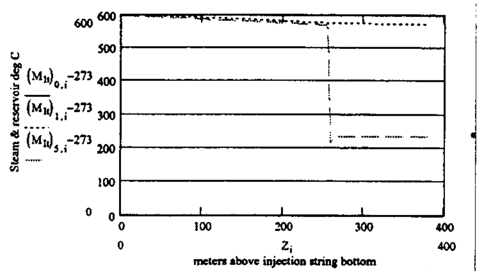


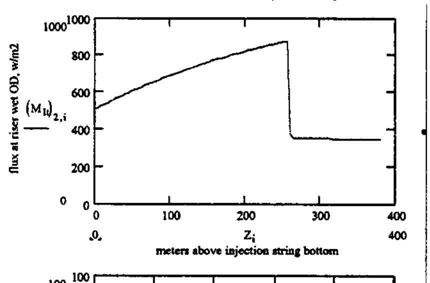


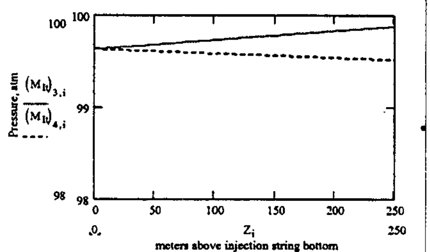


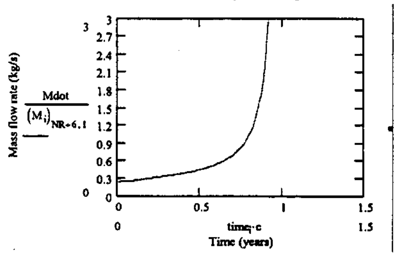


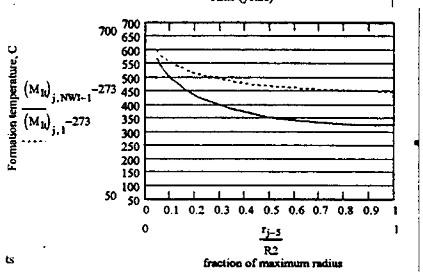
******************* START STEAM CASE 11 **************************

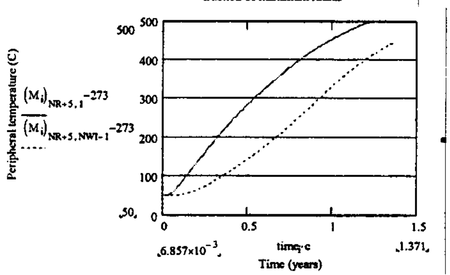




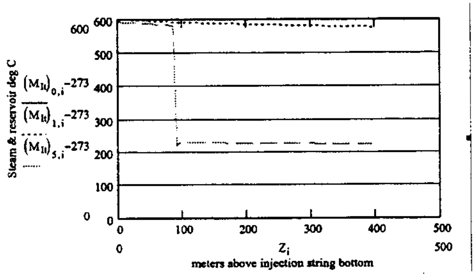


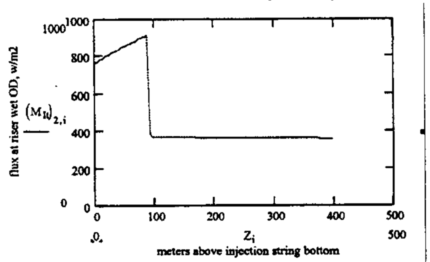


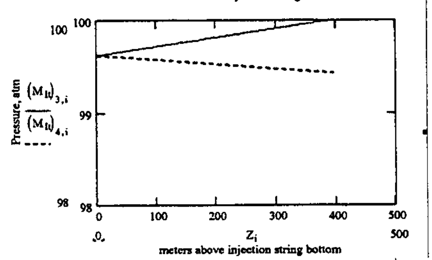


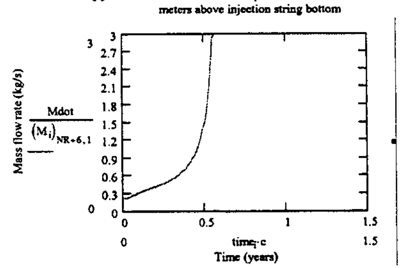


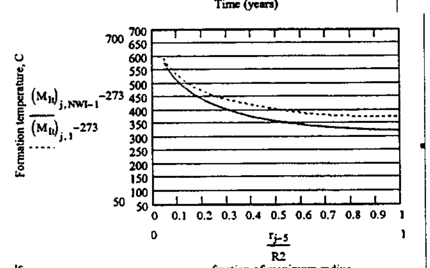
******************* START STEAM CASE 12 ***************************

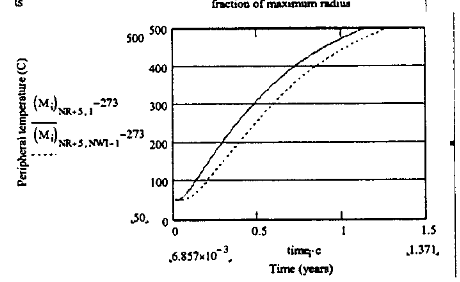




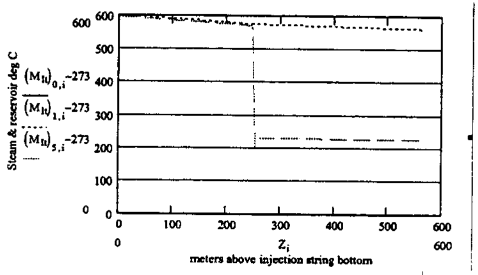


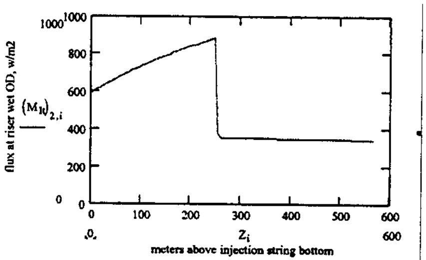


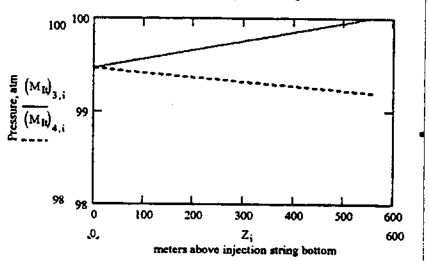


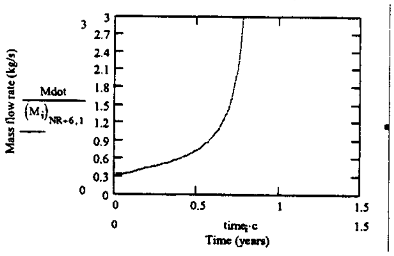


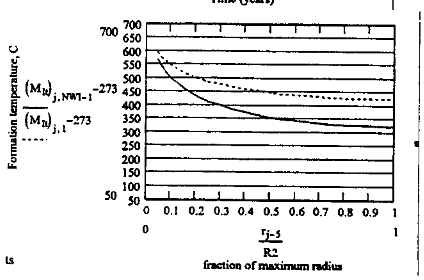
******************** START STEAM CASE 13 ****************************

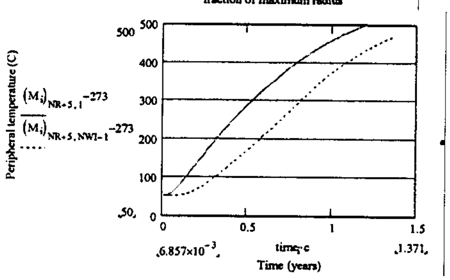




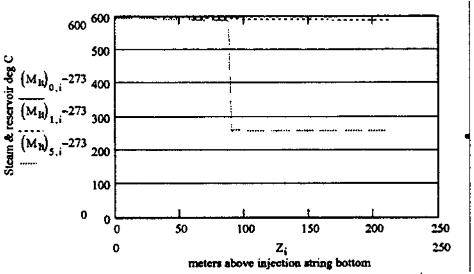


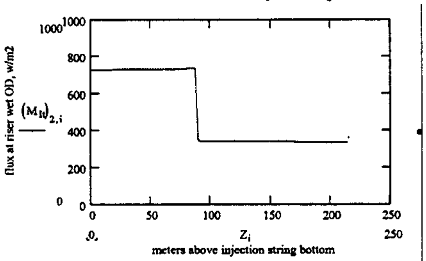


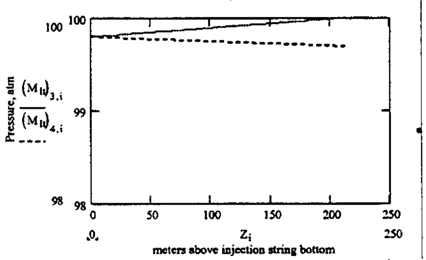


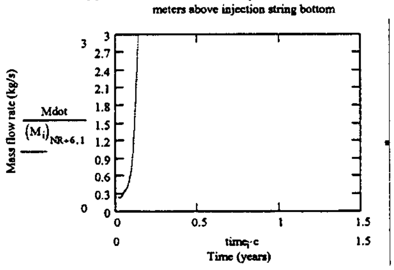


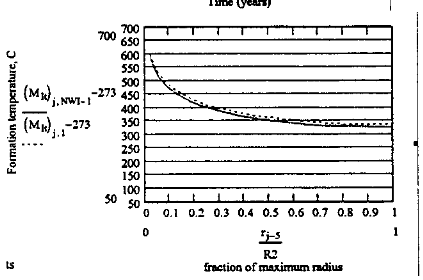
******************* START STEAM CASE 14 **************************



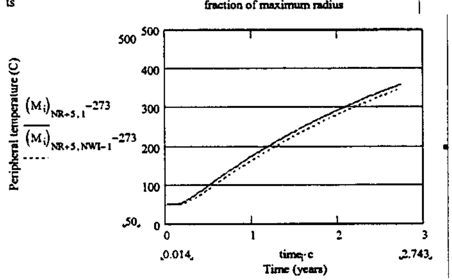




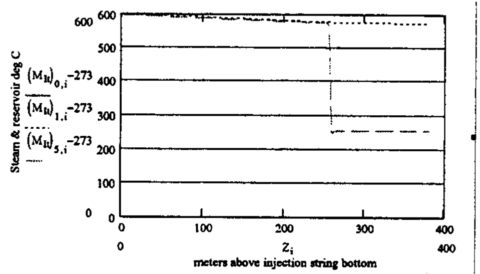


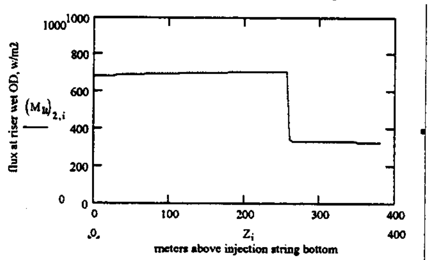


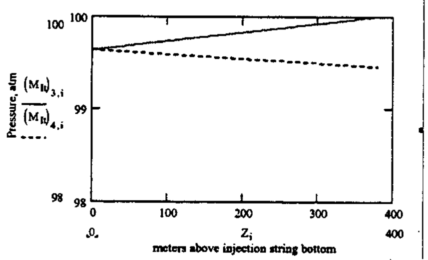
ts

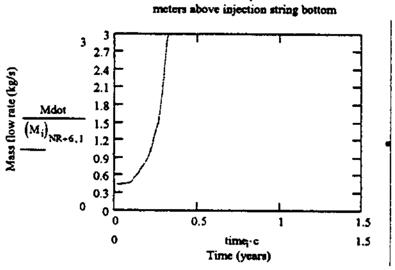


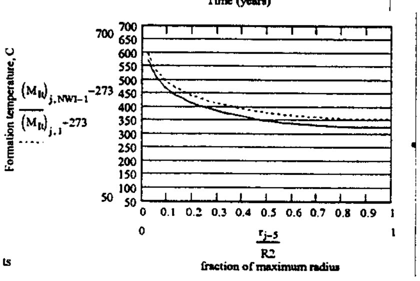
******************** START STEAM CASE 15 ****************************

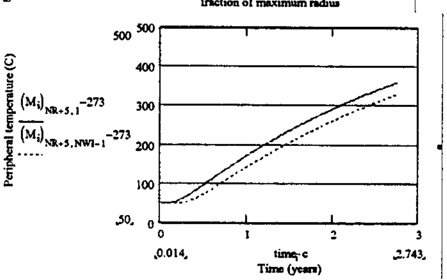




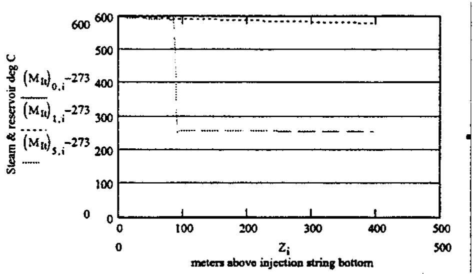


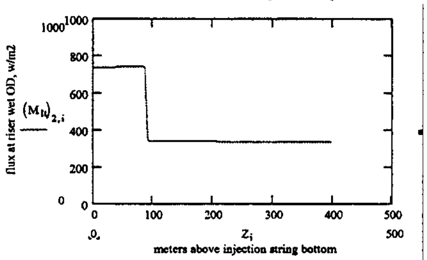


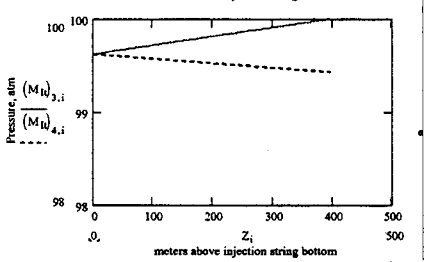


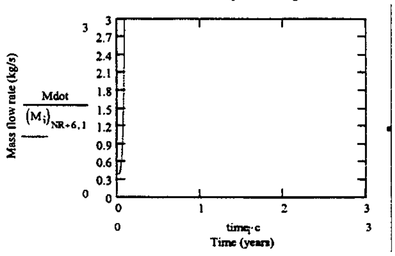


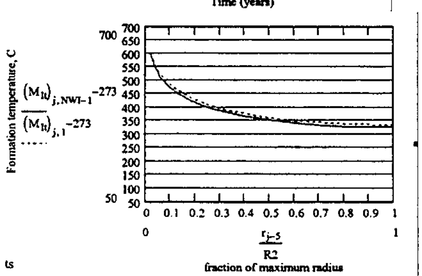
******************** START STEAM CASE 16 ****************************

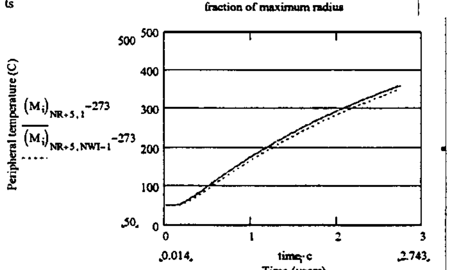




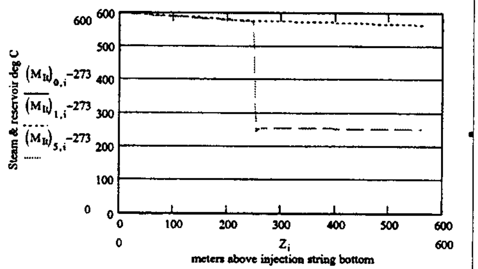


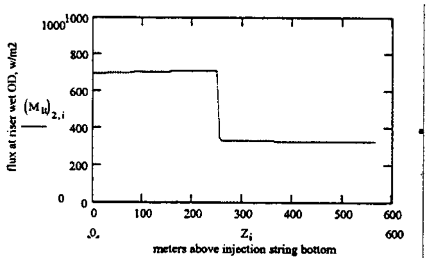


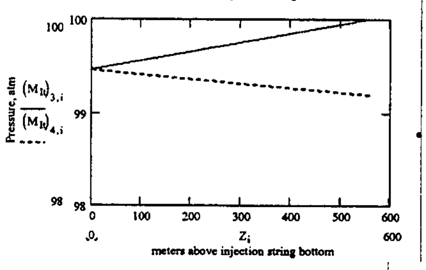


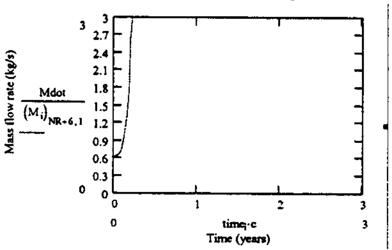


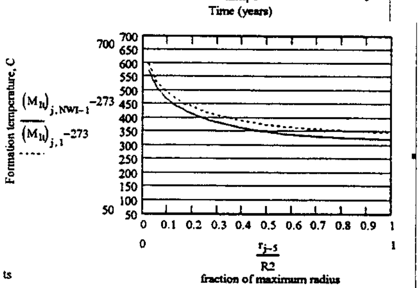
******************* START STEAM CASE 17 ***************************

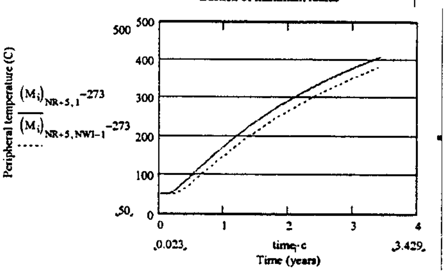




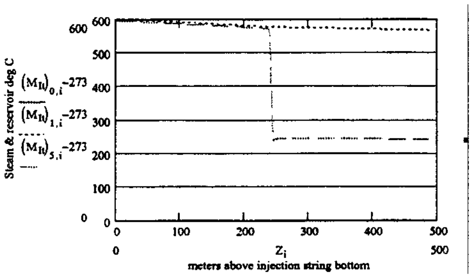


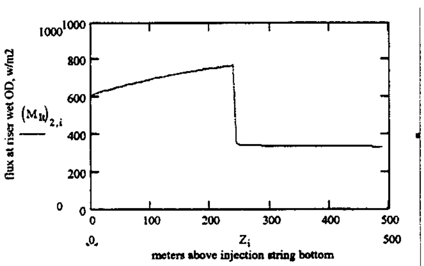


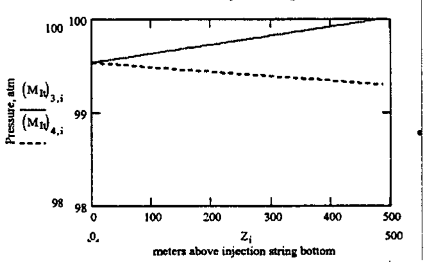


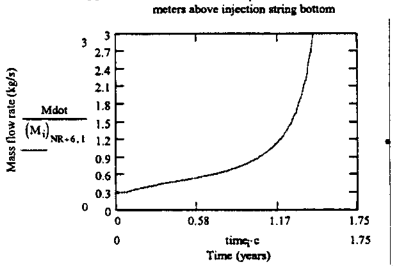


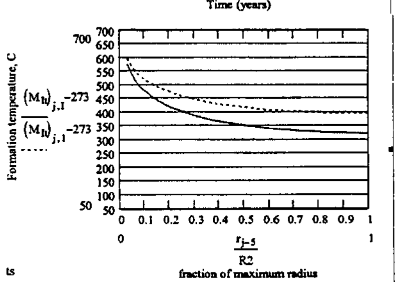
******************** START STEAM CASE 18 ***************************

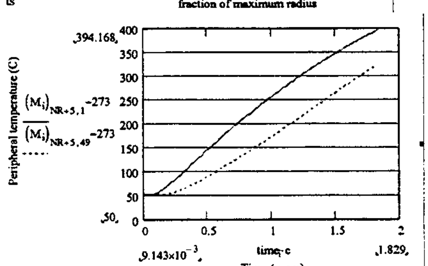












APPENDIX I: DOWNHOLE COMBUSTION PARAMETRIC STUDY

******************** START DHC CASE 1 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1..Npts \quad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \quad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \quad Ns_i := ceil(ns_i) \quad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

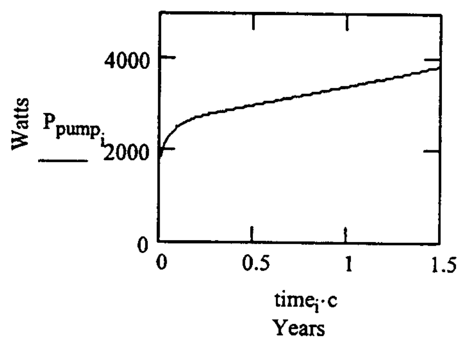
$$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump_{It}} = 4.378 \times 10^3 \, watt$$

check size of V^2 term...

$$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.189 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$$

$Vout = 15.791 m sec^{-1}$

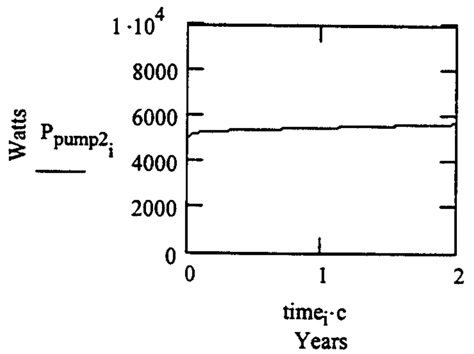
$$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 0.069 hp$$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

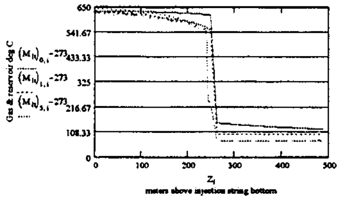
$i := 1..Npts \quad ratio_i := (M_i)_{4,NW} \quad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \quad Ns_i := ceil(ns_i) \quad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump2_{It}} = 5.686 \times 10^3 \, watt$$



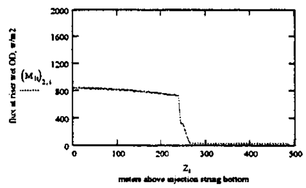
PLOTS $tmax = 1.8 \times 10^{4}\,hr$ $Nt = 2.25 \times 10^{3}$ $Nsfrq = 10$ $Npts = 225$ $It = 225$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 1.8 \times 10^{4}\,hr$



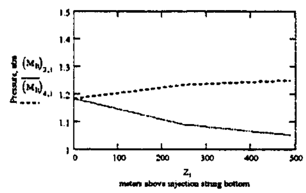
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 243.84m$

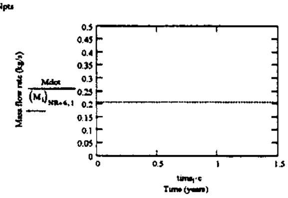


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 1.06 \cdot 10^{4} \\ 1.845 \cdot 10^{5} \end{pmatrix}$$

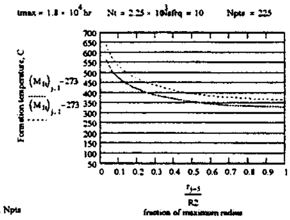


$i := 1..Npts$

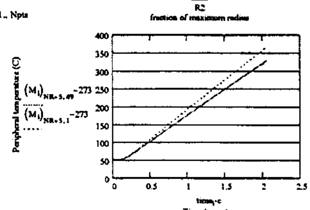


$I := 49$ **(# steps above well bottom)** $j := 5..NR + 5$

$tmax = 1.8 \cdot 10^{4}\,hr$ $Nt = 2.25 \times 10^{3}$ $Nsfrq = 10$ $Npts = 225$ $It = 225$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 225$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 \cdot (M_{It})_{0,NW} - 0.5 \cdot (M_{It-1})_{0,NW} \right] \cdot K \right] + Q \cdot Nsfrq \cdot It \cdot \Delta t \right]$$

$Ein = 1.286 \cdot 10^{13}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$ **Based on reservoir ΔTs**

$\Delta ER = 1.226 \cdot 10^{13}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.046$

******************** START DHC CASE 2 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1..Npts \qquad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

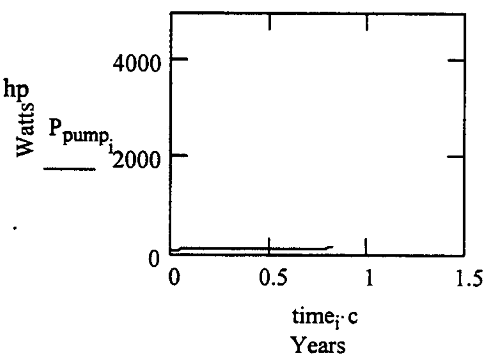
$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma-1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump_{It}} = 126.184watt$

check size of V^2 term...

$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.015 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$

$Vout = 5.706msec^{-1}$

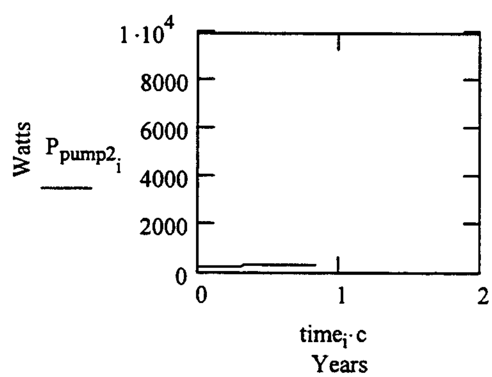
$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 3.379 \times 10^{-3} hp$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

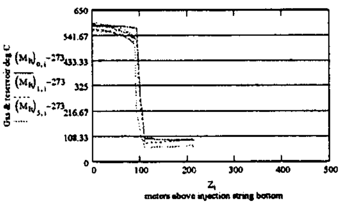
$i := 1..Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma-1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump2_{It}} = 255.956watt$



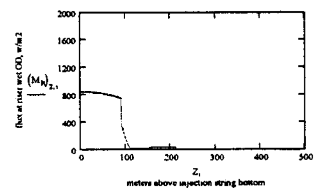
PLOTS $tmax = 7.2\cdot 10^3\,hr$ $Nt = 900$ $Nsfrq = 10$ $Npts = 90$ $It = 90$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 7.2\times 10^3\,hr$



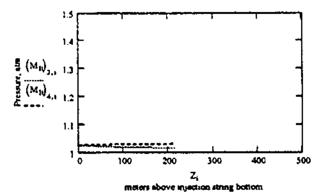
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

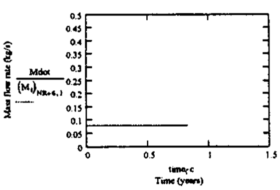


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 5.279\times 10^3 \\ 7.029\times 10^4 \end{pmatrix}$$

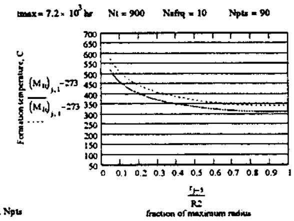


$i := 1..Npts$

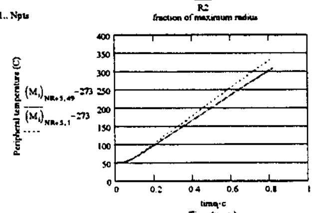


$I := 49$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 7.2\cdot 10^3\,hr$ $Nt = 900$ $Nsfrq = 10$ $Npts = 90$ $It = 90$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 90$

$$Ein := MdotCp\cdot Nsfrq\cdot \Delta t\cdot \sum_{i=1}^{It-1}\left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot \Delta t\cdot\left[Ts - \left[1.5(M_{It})_{0,NW} - 0.5(M_{It-1})_{0,NW}\right]\cdot K\right] + Q\cdot Nsfrq\cdot It\cdot \Delta t\right]$$

$Ein = 1.974\times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\cdot \Delta z\cdot \pi\cdot \sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot \sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2}\cdot K - Tw_i\right]$$ **Based on reservoir ΔTs**

$\Delta ER = 1.899\cdot 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.038$

$Ew :=$
```
Q0 ← 0
Q1 ← 0
for I ∈ 1..It
    i ← 1
    while i ≤ NW
        j ← if(i > NW1, 0, 1)
            [(M_I)_[illegible] + (M_I)_[illegible]] ΔdZ_i
```

Based on riser OD flux

$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t = 1.956\times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.059$ **overburden fraction**

$\frac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t}{[illegible]} - 1 = -9.368\times 10^{-3}$

******************** START DHC CASE 3 ********************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1 .. Npts \qquad ratio_i := \dfrac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \dfrac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

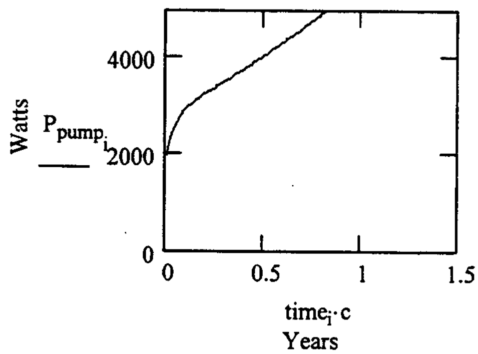
$$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump_{It}} = 5.234 \times 10^3 \text{ watt}$$

check size of V^2 term...

$$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.199 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$$

$Vout = 18.884 m sec^{-1}$

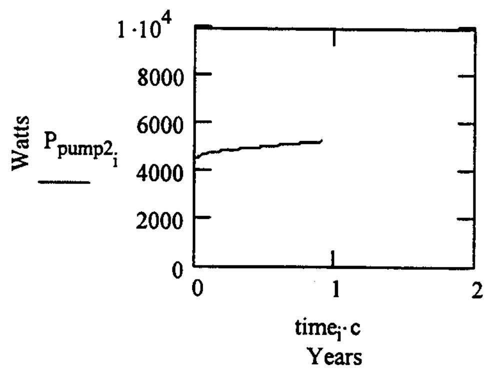
$$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 0.105 hp$$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

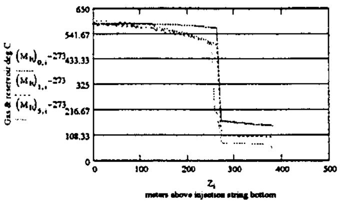
$i := 1 .. Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \dfrac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump2_{It}} = 5.259 \times 10^3 \text{ watt}$$



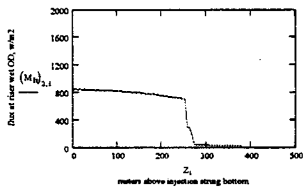
PLOTS $tmax = 7.92 \times 10^{3}\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 7.92 \times 10^{3}\,hr$



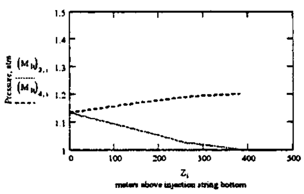
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
6+ : formation

$z_{shale} = 259.08m$

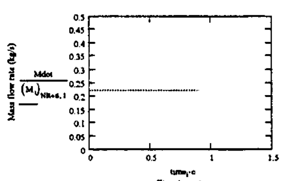


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 6.885 \times 10^{3} \\ 1.935 \times 10^{5} \end{pmatrix}$$

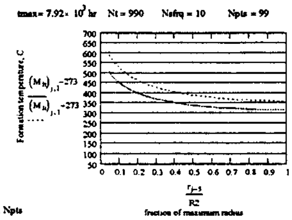


$i := 1..Npts$

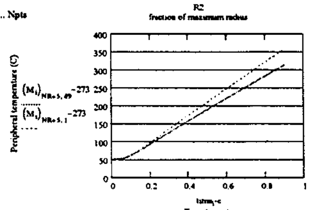


$I := 49$ **(# steps above well bottom)** $j := 5..NR + 5$

$tmax = 7.92 \times 10^{3}\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 90$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 99$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on air ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{0,NW} - 0.5 (M_{It-1})_{0,NW} \right] \cdot K \right] + Q \cdot Nsfrq \cdot It \cdot \Delta t \right]$$

$Ein = 5.863 \times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \, \Delta z \, \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 5.469 \times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.067$

$Ew :=$ | $Q_0 \leftarrow 0$
| $Q_1 \leftarrow 0$
| for $I \in 1..It$
| | $i \leftarrow 1$
| | while $i \le NW$
| | | $j \leftarrow if(i > NW1, 0, 1)$
| | | $Q_j \leftarrow \left[(M_I)_{(2,i-1)} + (M_I)_{(2,i)} \right] AdZ_j$ ...

Based on riser OD flux

$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 5.808 \times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.028$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = -9.462 \times 10^{-3}$

********************** START DHC CASE 4 *********************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$$i := 1..Npts \qquad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$$

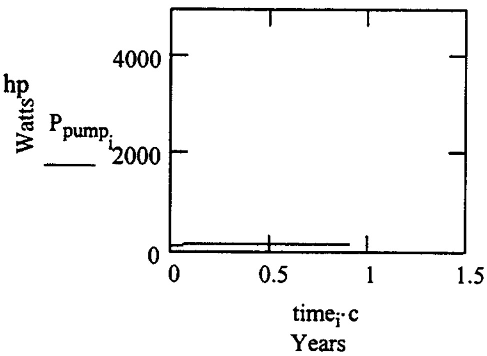
$$Ppump_i := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad Ppump_{It} = 164.345watt$$

check size of V^2 term...

$$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.02 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$$

$$Vout = 5.256msec^{-1}$$

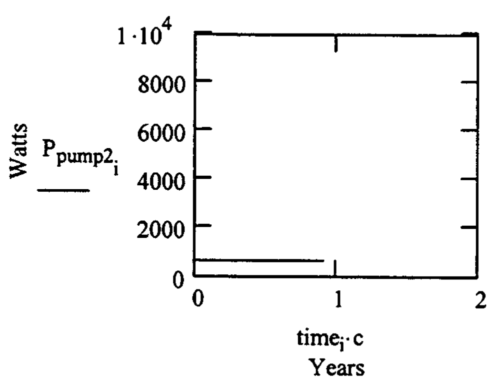
$$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 2.868 \times 10^{-3} hp$$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

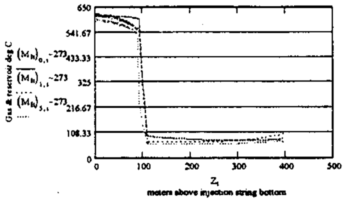
$$i := 1..Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$$

$$Ppump2_i := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad Ppump2_{It} = 644.522watt$$



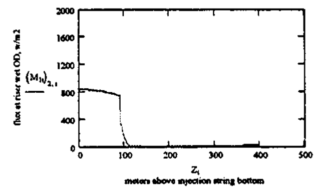
PLOTS $tmax = 7.92\times 10^{3}\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 7.92\times 10^{3}\,hr$



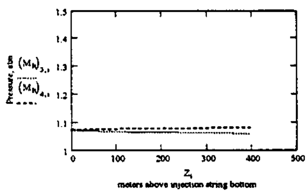
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

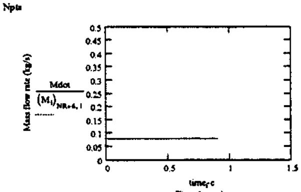


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 6.809\times 10^{3} \\ 7.001\times 10^{4} \end{pmatrix}$$

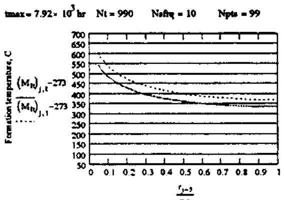


$i := 1..Npts$

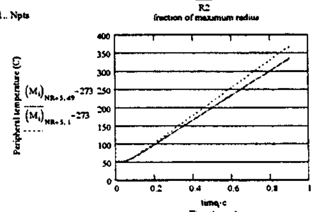


$I := 49$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 7.92\times 10^{3}\,hr$ $Nt = 990$ $Nsfrq = 10$ $Npts = 99$ $It = 99$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 99$

$$Ein := MdotCp\cdot Nsfrq\cdot \Delta t\cdot \sum_{i=1}^{It-1}\left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot \Delta t\cdot \left[Ts - \left[1.5(M_{It})_{0,NW} - 0.5(M_{It-1})_{0,NW}\right]\cdot K\right] + Q\cdot Nsfrq\cdot It\cdot \Delta t\right]$$

$Ein = 2.2\times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\,\Delta z\,\pi\cdot \sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot \sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2}\cdot K - Tw_i\right]$$ **Based on reservoir ΔTs**

$\Delta ER = 2.118\times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.037$

$Ew :=$ | $Q_0 \leftarrow 0$
| $Q_1 \leftarrow 0$
| for $I \in 1..It$
| | $i \leftarrow 1$
| | while $i \le NW$
| | | $j \leftarrow if(i > NW1, 0, 1)$
| | | $\left[(M_I)_{\ldots} + (M_I)_{\ldots}\right]\,AdZ_i$

Based on riser OD flux

$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t = 2.179\times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.073$ **overburden fraction**

$\frac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t}{\ldots} - 1 = -9.306\times 10^{-3}$

******************** START DHC CASE 5 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1 .. Npts \qquad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

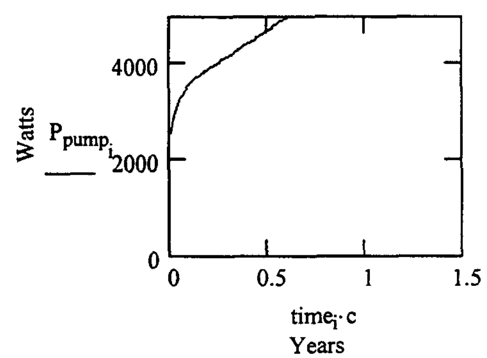
$$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump_{It}} = 5.902 \times 10^3\ watt$$

check size of V^2 term...

$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.24 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$

$Vout = 17.756 m sec^{-1}$

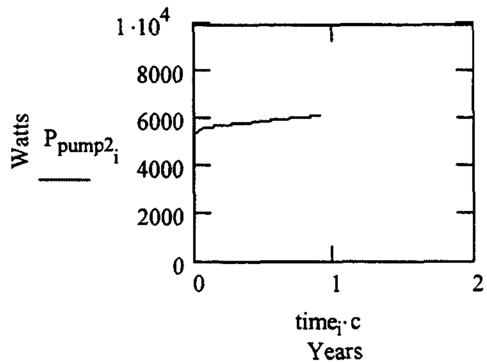
$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 0.093 hp$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

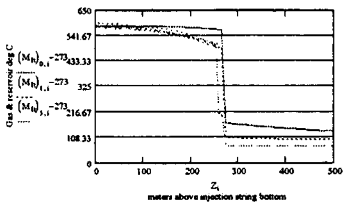
$i := 1 .. Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump2_{It}} = 6.13 \times 10^3\ watt$$



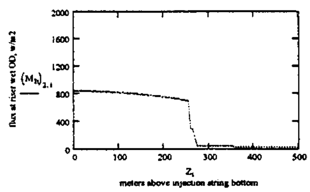
PLOTS tmax = $7.92 \cdot 10^3$ hr Nt = 990 Nafrq = 10 Npts = 99 It = 99 i := 0.. NW

timeplot := It·Nafrq·Δt timeplot = $7.92 \cdot 10^3$ hr



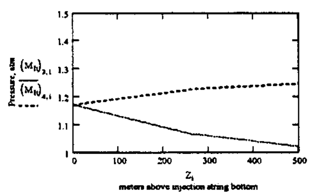
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

z_{shale} = 259.08m

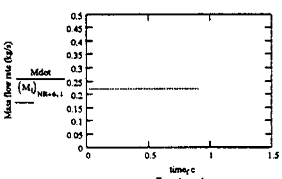


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 1.227 \cdot 10^4 \\ 1.936 \cdot 10^5 \end{pmatrix}$$

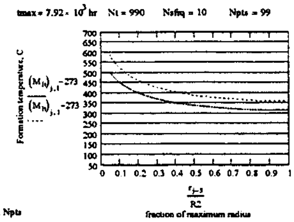


i := 1.. Npts

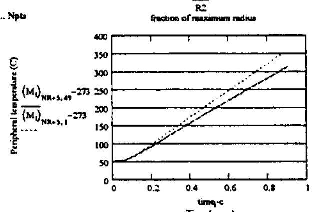


I := 49 **(# steps above well bottom)** j := 5.. NR + 5

tmax = $7.92 \cdot 10^3$ hr Nt = 990 Nafrq = 10 Npts = 99 It = 99



i := 1.. Npts



SYSTEM ENERGY BALANCE APPROXIMATE CHECK It = 99

$$Ein := MdotCp \cdot Nafrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nafrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{0,NW} - 0.5 (M_{It-1})_{0,NW} \right] \cdot K \right] + Q \cdot Nafrq \cdot It \cdot \Delta t \right]$$

$Ein = 5.994 \cdot 10^{12}$ joule

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$ **Based on reservoir ΔTs**

$\Delta ER = 5.597 \cdot 10^{12}$ joule $\frac{\Delta ER}{Ein} - 1 = -0.066$

Ew := | $Q_0 \leftarrow 0$
| $Q_1 \leftarrow 0$
| for I ∈ 1.. It
| | i ← 1
| | while i ≤ NW
| | | j ← if(i > NW1, 0, 1)
| | | $\left[(M_I)_{(?, i-1)} + (M_I)_{(?, i)} \right]$ AdZ$_i$

Based on riser OD flux

$(Ew_0 + Ew_1) \cdot watt \cdot Nafrq \cdot \Delta t = 5.938 \cdot 10^{12}$ joule

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.05$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nafrq \cdot \Delta t}{\ldots} - 1 = -9.326 \cdot 10^{-3}$

******************** START DHC CASE 6 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1..Npts \qquad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

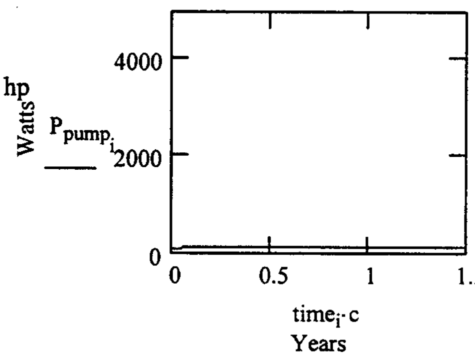
$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump_{It}} = 136.452watt$

check size of V^2 term...

$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.016 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$

$Vout = 5.721msec^{-1}$

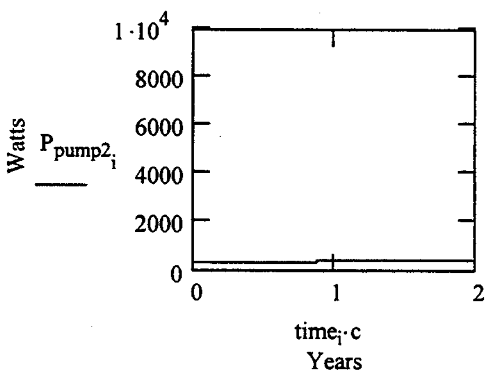
$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 3.397\times 10^{-3}hp$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

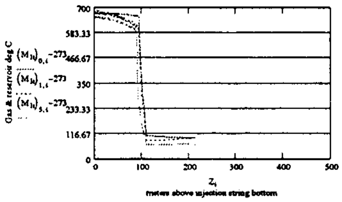
$i := 1..Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump2_{It}} = 343.948watt$



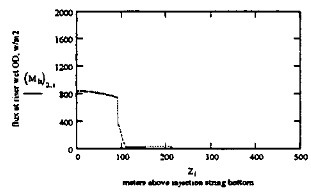
PLOTS $tmax = 3.168\cdot 10^{4}\,hr$ $Nt = 3.96\times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 3.168\cdot 10^{4}\,hr$



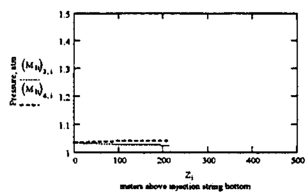
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

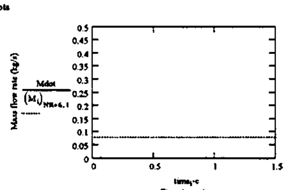


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 5.553\cdot 10^{3} \\ 6.965\cdot 10^{4} \end{pmatrix}$$

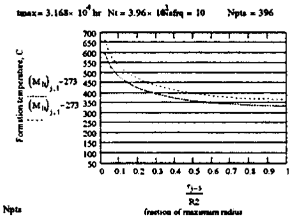


$i := 1..Npts$

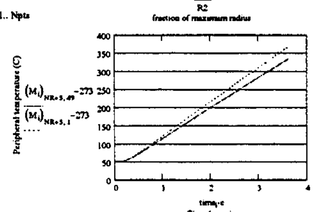


$I := 49$ **(# steps above well bottom)** $j := 5..NR+5$

$tmax = 3.168\times 10^{4}\,hr$ $Nt = 3.96\times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 396$

$$Ein := MdotCp\cdot Nsfrq\cdot \Delta t\cdot \sum_{i=1}^{It-1}\left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot \Delta t\left[Ts - \left[1.5(M_{It})_{0,NW} - 0.5(M_{It-1})_{0,NW}\right]K\right] + Q\cdot Nsfrq\cdot It\cdot \Delta t\right]$$

$Ein = 8.653\cdot 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\,\Delta z\,\pi\cdot \sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot \sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2}\cdot K - Tw_i\right]$$ **Based on reservoir ΔTs**

$\Delta ER = 8.343\times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.036$

$Ew :=$ | $Q_0 \leftarrow 0$
| $Q_1 \leftarrow 0$
| for $I \in 1..It$
| | $i \leftarrow 1$
| | while $i \le NW$
| | | $j \leftarrow if(i > NW1, 0, 1)$
| | | $Q_j \leftarrow \left[\frac{(M_I)_{(2,i-1)} + (M_I)_{(2,i)}}{}\right]\frac{AdZ_j}{} + Q$ …

Based on riser OD flux

$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t = 8.571\times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.063$ **overburden fraction**

$\frac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t}{Ein} - 1 = -9.451\times 10^{-3}$

******************** START DHC CASE 7 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$$i := 1..\,Npts \qquad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$$

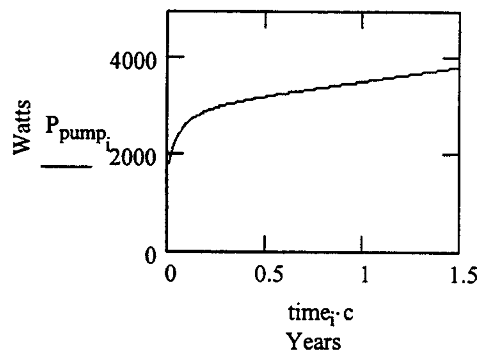
$$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump_{It}} = 5.289 \times 10^3\ watt$$

check size of V^2 term...

$$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.197 \qquad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$$

$$Vout = 18.466\,m\,sec^{-1}$$

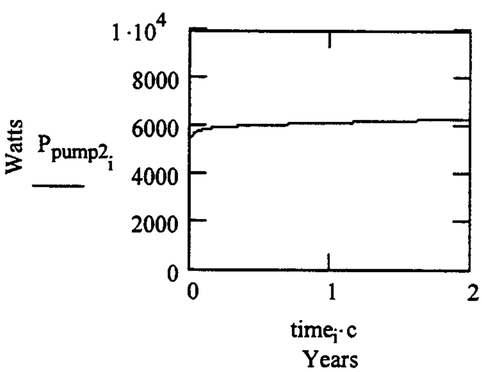
$$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 0.1\,hp$$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

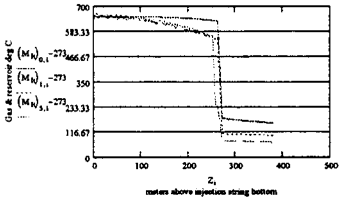
$$i := 1..\,Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$$

$$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump2_{It}} = 6.605 \times 10^3\ watt$$



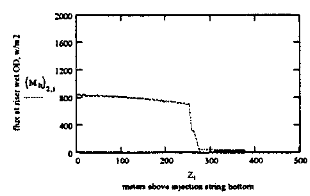
PLOTS $tmax = 3.168 \times 10^{4}\,hr$ $Nt = 3.96 \times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$ $i := 0..NW$

$timeplot := It \cdot Nsfrq \cdot \Delta t$ $timeplot = 3.168 \times 10^{4}\,hr$



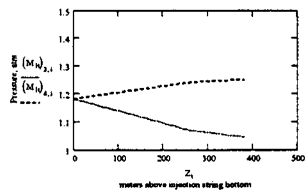
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 259.08\,m$

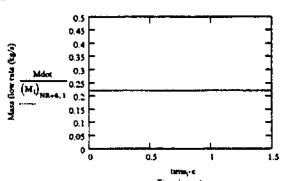


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.069 \times 10^{3} \\ 1.912 \times 10^{5} \end{pmatrix}$$

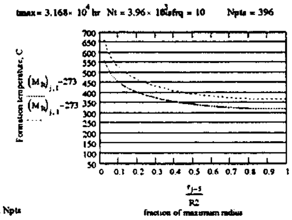


$i := 1..Npts$

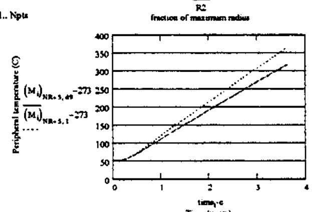


$I := 49$ **(# steps above well bottom)** $j := 5..NR + 5$

$tmax = 3.168 \times 10^{4}\,hr$ $Nt = 3.96 \times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 396$

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{0,NW} - 0.5 (M_{It-1})_{0,NW} \right] \cdot K \right] + Q \cdot Nsfrq \cdot It \cdot \Delta t \right]$$

$Ein = 2.321 \times 10^{13}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\,\Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$ **Based on reservoir ΔTs**

$\Delta ER = 2.218 \times 10^{13}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.044$

$Ew :=$
$Q_0 \leftarrow 0$
$Q_1 \leftarrow 0$
for $I \in 1..It$
$i \leftarrow 1$
while $i \le NW$
$j \leftarrow if(i > NW1, 0, 1)$
$\left[(M_I)_{(2,i-1)} + (M_I)_{(2,i)} \right] AdZ_j$

Based on riser OD flux

$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 2.298 \times 10^{13}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.029$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{Ein} - 1 = -9.74 \times 10^{-3}$

******************** START DHC CASE 8 ********************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1 .. Npts \quad ratio_i := \frac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \quad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \quad Ns_i := ceil(ns_i) \quad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

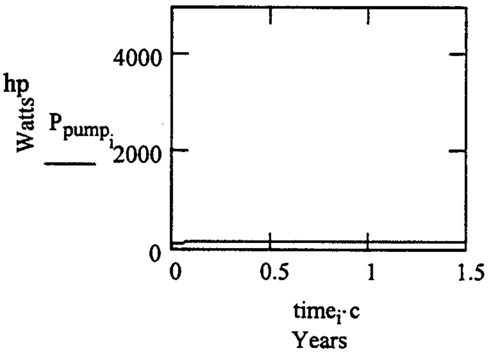
$P_{pump_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump_{It}} = 172.206watt$

check size of V^2 term...

$\frac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.021 \quad Vout := \frac{Mdot}{(M_{It})_{NR+6,1}} \cdot \frac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$

$Vout = 5.283msec^{-1}$

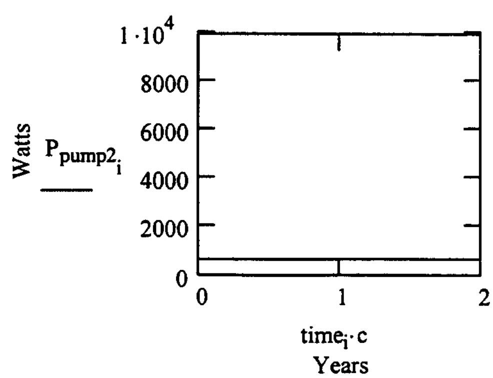
$\frac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 2.897 \times 10^{-3} hp$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

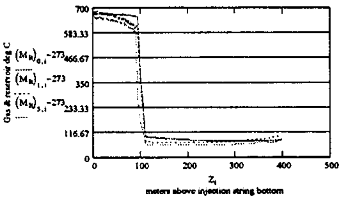
$i := 1 .. Npts \quad ratio_i := (M_i)_{4,NW} \quad ns_i := \frac{\ln(ratio_i)}{\ln(3)} \quad Ns_i := ceil(ns_i) \quad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$P_{pump2_i} := \frac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \frac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1\right] \qquad P_{pump2_{It}} = 647.205watt$



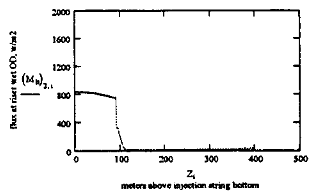
PLOTS $tmax = 3.168\times 10^{4}\,hr$ $Nt = 3.96\times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$ $i := 0..NW$

$timeplot := It\cdot Nsfrq\cdot \Delta t$ $timeplot = 3.168\times 10^{4}\,hr$



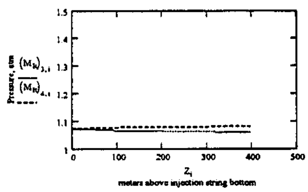
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

$z_{shale} = 91.44m$

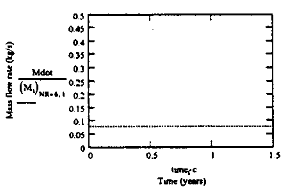


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 7.087\times 10^{3} \\ 6.96\times 10^{4} \end{pmatrix}$$

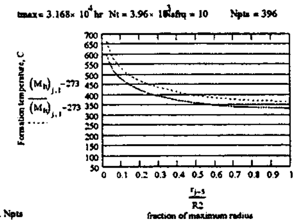


$i := 1..Npts$

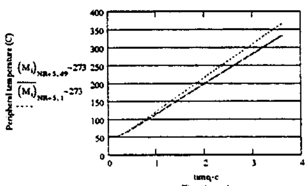


$I := 49$ (# steps above well bottom) $j := 5..NR + 5$

$tmax = 3.168\times 10^{4}\,hr$ $Nt = 3.96\times 10^{3}$ $Nsfrq = 10$ $Npts = 396$ $It = 396$



$i := 1..Npts$



SYSTEM ENERGY BALANCE APPROXIMATE CHECK $It = 396$

$$Ein := MdotCp\cdot Nsfrq\cdot \Delta t\cdot \sum_{i=1}^{It-1}\left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2}\cdot K}{(M_i)_{NR+6,1}}\right]$$ **Based on air ΔT and MdotCp;**

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}}\cdot Nsfrq\cdot \Delta t\cdot\left[Ts - \left[1.5(M_{It})_{0,NW} - 0.5(M_{It-1})_{0,NW}\right]\cdot K\right] + Q\cdot Nsfrq\cdot It\cdot \Delta t\right]$$

$Ein = 8.785\times 10^{12}\,joule$

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp\,\Delta z\,\pi\cdot \sum_{j=0}^{NR-1}\left[(r_{j+1})^2 - (r_j)^2\right]\cdot\sum_{i=0}^{NW}\left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2}\cdot K - Tw_i\right]$$ **Based on reservoir ΔTs**

$\Delta ER = 8.471\times 10^{12}\,joule$ $\frac{\Delta ER}{Ein} - 1 = -0.036$

```
Ew:= | Q0 ← 0
     | Q1 ← 0
     | for I ∈ 1..It
     |   | i ← 1
     |   | while i ≤ NW
     |   |   | j ← if(i > NWI,0,1)
     |   |   |     [(M_I)(2,i-1) + (M_I)(2,i)] AdZ_i
```

Based on riser OD flux

$(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t = 8.703\times 10^{12}\,joule$

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.077$ overburden fraction

$\frac{(Ew_0 + Ew_1)\cdot watt\cdot Nsfrq\cdot \Delta t}{\ldots} - 1 = -9.325\times 10^{-3}$

******************** START DHC CASE 9 ******************************

Pressure loss compressor power (H&R, p377, neglecting V^2 terms)

$i := 1..\,Npts \qquad ratio_i := \dfrac{(M_i)_{4,NW}}{(M_i)_{3,NW}} \qquad ns_i := \dfrac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

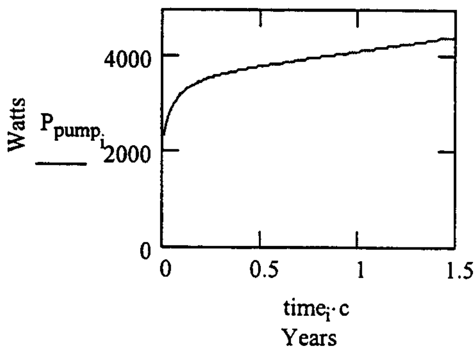
$P_{pump_i} := \dfrac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \dfrac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump_{It}} = 5.963 \times 10^3\, watt$

check size of V^2 term...

$\dfrac{(M_{It})_{4,NW}}{(M_{It})_{3,NW}} = 1.237 \qquad Vout := \dfrac{Mdot}{(M_{It})_{NR+6,1}} \cdot \dfrac{1}{\rho\left[(M_{It})_{3,NW} \cdot atm, (M_{It})_{0,NW} \cdot K\right] \cdot AxR_0}$

$Vout = 17.382 m sec^{-1}$

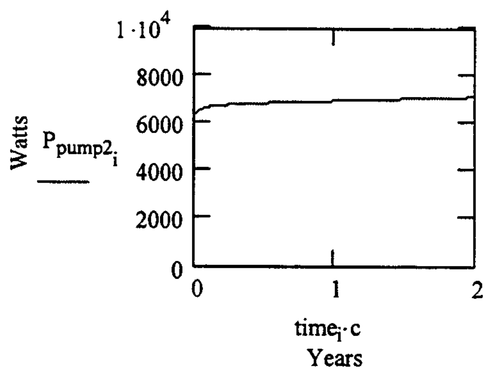
$\dfrac{Mdot}{(M_{It})_{NR+6,1}} \cdot Vout^2 = 0.089 hp$



Atmosphere to heater compressor power (H&R, p377, neglecting V^2 terms)

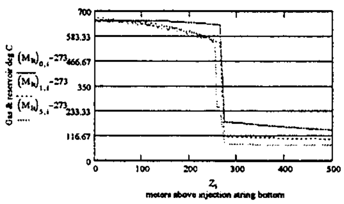
$i := 1..\,Npts \qquad ratio_i := (M_i)_{4,NW} \qquad ns_i := \dfrac{\ln(ratio_i)}{\ln(3)} \qquad Ns_i := ceil(ns_i) \qquad Ratio_i := (ratio_i)^{\frac{1}{Ns_i}}$

$P_{pump2_i} := \dfrac{Ns_i \cdot Mdot}{(M_i)_{NR+6,1}} \cdot \dfrac{\gamma}{\gamma - 1} \cdot Rgas \cdot (M_i)_{0,NW} \cdot K \cdot \left[(Ratio_i)^{1-\frac{1}{\gamma}} - 1 \right] \qquad P_{pump2_{It}} = 7.392 \times 10^3\, watt$



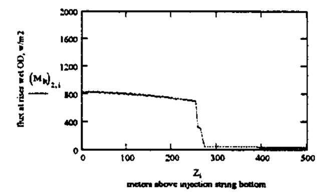
PLOTS tmax = 3.24×10^4 hr Nt = 4.05×10^3 Nsfrq = 10 Npts = 405 It = 405 i := 0.. NW

timeplot := It·Nsfrq·Δt timeplot = 3.24×10^4 hr



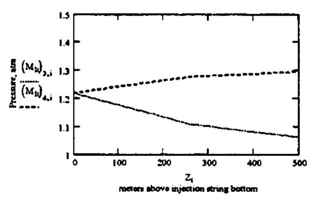
0 : inner stream
1 : outer stream
2 : flux to well bore
3 : inner P
4 : outer P
5+ : formation

z_{shale} = 259.08m

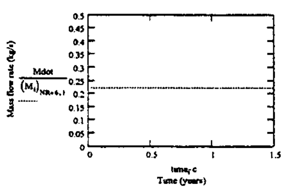


Instantaneous Overburden loss, Shale heating, Watts...

$$Qw = \begin{pmatrix} 1.272 \times 10^4 \\ 1.912 \times 10^5 \end{pmatrix}$$

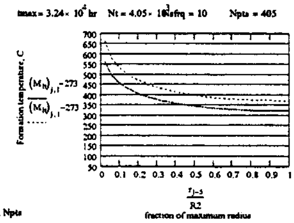


i := 1.. Npts

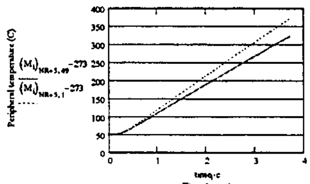


I := 49 **(# steps above well bottom)** j := 5.. NR + 5

tmax = 3.24×10^4 hr Nt = 4.05×10^3 Nsfrq = 10 Npts = 405 It = 405



i := 1.. Npts



SYSTEM ENERGY BALANCE APPROXIMATE CHECK It = 405

$$Ein := MdotCp \cdot Nsfrq \cdot \Delta t \cdot \sum_{i=1}^{It-1} \left[\frac{Ts - \frac{(M_i)_{0,NW} + (M_{i+1})_{0,NW}}{2} \cdot K}{(M_i)_{NR+6,1}} \right]$$

Based on air ΔT and MdotCp;

$$Ein := Ein + \left[\frac{MdotCp}{(M_{It})_{NR+6,1}} \cdot Nsfrq \cdot \Delta t \cdot \left[Ts - \left[1.5 (M_{It})_{0,NW} - 0.5 (M_{It-1})_{0,NW} \right] \cdot K \right] + Q \cdot Nsfrq \cdot It \cdot \Delta t \right]$$

$Ein = 2.43 \times 10^{13}$ joule

"Ein" sum based on fact that temp at i=1 is really t=0 result, so we have to extrapolate last point to midpoint of interval It-1 to It

---

$$\Delta ER := CRp \cdot \Delta z \cdot \pi \cdot \sum_{j=0}^{NR-1} \left[(r_{j+1})^2 - (r_j)^2 \right] \cdot \sum_{i=0}^{NW} \left[\frac{(M_{It})_{j+5,i} + (M_{It})_{j+6,i}}{2} \cdot K - Tw_i \right]$$

Based on reservoir ΔTs

$\Delta ER = 2.324 \times 10^{13}$ joule $\frac{\Delta ER}{Ein} - 1 = -0.044$

$$Ew := \begin{array}{|l} Q_0 \leftarrow 0 \\ Q_1 \leftarrow 0 \\ \text{for } I \in 1..It \\ \quad \begin{array}{|l} i \leftarrow 1 \\ \text{while } i \le NW \\ \quad \begin{array}{|l} j \leftarrow \text{if}(i > NW1, 0, 1) \end{array} \end{array} \end{array}$$

Based on riser OD flux

$(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t = 2.407 \times 10^{13}$ joule

$\frac{Ew_0}{Ew_0 + Ew_1} = 0.053$ **overburden fraction**

$\frac{(Ew_0 + Ew_1) \cdot watt \cdot Nsfrq \cdot \Delta t}{\ldots} - 1 = -9.532 \times 10^{-3}$

APPENDIX J: ECONOMIC COMPARISON OF MOLTEN SALT AND ELECRIC HEATING

SOLAR- & NON-SOLAR-POWERED SUB-SURFACE HEAT DELIVERY VIA MOLTEN NITRATE SALT OR STEAM

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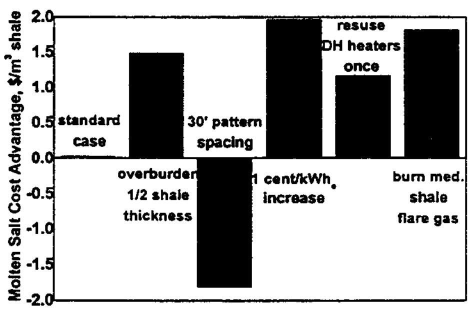
System descriptions: We have considered two sensible-heat methods for delivering heat to subsurface formations – molten nitrate salt and steam. These systems consist of heaters, pumps and piping, and down-hole piping. The heaters are either solar or combustion powered. We contrast these systems with downhole electric heaters. Downhole electric heaters require, in addition to the downhole resistance heaters, an electric plant and distribution lines. There are two critical differences between these approaches: (1) sensible-heat methods avoid electric-conversion expenses (but incur heat losses in the heater, distribution system, and overburden); and (2) sensible-heat methods will not overheat the well adjacent to low-conductivity zones.

Salt vs. steam: We have modeled subsurface sensible heating using both molten salt and steam. At similar mass flow rates, heating results are comparable, but piping flow losses are problematic for steam. To limit losses, operation at 100 atmospheres is needed. A high-temperature steam compressor will be required in a closed-loop system to overcome piping losses. Heating a cold formation will introduce condensation, and fundamental changes in flow behavior. The primary advantage of steam relative to salt is elimination of any potential for freezing. However, there are a number of strategies for avoiding salt freezing, including impedance or resistance heating, and controlling the freezing point by salt hydration/dehydration. On balance, therefore, we favor molten salt over steam.

Combustion-heated salt vs. downhole electric heaters: We have evaluated heating shale with combustion-heated salt vs. downhole electric heaters powered by metered electricity. We obtained energy usage from our subsurface heating model, and hardware costs from vendors (except: $37k for an 800' heater, from Shell). We performed parametric studies around a standard case, which is 800' of overburden, 800' of shale, 6" casing, 40' pattern spacing, 2.7¢ per kWe, and 27¢ per therm natural gas. We found that the energy invested in the oil shale was ~0.7 GJ/m^3 for all cases. For the standard case, we found a resistance-heating total cost of \$6.55 per m^3 of shale, and a cost advantage for molten salt of \$0.026/m^3. For other cases, the advantage was: (a) \$1.49/m^3 whenever the overburden was ½ the shale thickness; (b) -\$1.82/m^3 if the pattern spacing decreased to 30'; (c) \$1.97/m^3 if the cost of electricity increased by 1¢/kWe; (d) \$1.17/m^3 if the downhole heaters (both electric and salt) can be reused once; (e) 1.82/m^3 if gas from medium-grade shale that otherwise would be flared supplements the natural gas. Combinations of the positive effects will give larger advantages. Additionally, the fragility of electric heaters relative to molten salt piping may require heater replacements, further favoring molten salt.



Solar-Heated Molten-Salt: The cost of solar heat is most strongly influenced by the solar resources at the site in question[1], the capital cost of the system, and the financial cost of money[2] (as represented by the fixed charge rate). The adjacent table shows the projected range of cost for high and low values of these 3 parameters at a future, large-scale plant with an operational temperature range of 288 – 565 °C and limited thermal storage resulting in cyclic heat input to the shale or requiring hybridization with combustion heat. Increasing thermal storage size to permit heat delivery the majority of the time increases costs about 20%. Costs for smaller, near-term plants will be higher. The low-cost case is 1.1 times the standard-case cost of natural gas, while the high-cost case is 3.5 times this cost of gas.

Future Cost of Solar Heat	Low-Cost Case	Mid-Cost Case	High-Cost Case
Solar Resources (kWh/m^2-year)	2800	2150	1800
Capital Costs ($/kW$_t$)	340	390	440
Fixed Charge Rate	7%	9%	12%
Levelized Energy Cost (2001$/therm)	0.30	0.61	0.95

[1] Preliminary estimates of Piceance basin annual solar resources are 2,000 – 2,300 kWh/m^2.
[2] Existing 10% federal investment tax credits and accelerated 5-year depreciation probably apply to solar heat for shale oil recovery. This reduces the fixed charge rate and provides 'revenue' early in the project, potentially reducing the impact of the delay between capital expenditure and production of revenue-generating product. These benefits are included in the low-cost case only; if they were included in the mid-cost case, they would reduce the FCR to 7% and the LEC to \$0.48/therm.

Demonstration project: We have proposed a molten-salt demonstration project that has the objective of proving the downhole hardware and freeze-protection methods, and solving both anticipated and unanticipated problems, prerequisite to either combustion or solar-heated operations at the Shell location in Colorado. Activities include conceptual and detailed design work, specifying and installing test equipment (mechanical, electrical, and instrumentation/controls) at Sandia, and conducting the tests. Sandia operates the National Solar Thermal Test Facility (NSTTF), and has the personnel to perform these tests. Solar personnel have experience in molten salt, most notably at the 10 MW Solar Two plant in Barstow, CA. The solar department has the necessary analytical tools and testing capabilities as well as engineering and technician staff that are familiar with high temperature molten salt systems. Sandia's materials experts have studied, tested, and understand molten-salt material-compatibility issues. The NSTTF also has forklifts, cranes, a small machine shop, and instrumentation systems. Sandia has many other facilities, accessible to the NSTTF, such as precision machine shops, welding experts, etc. A cost estimate of $1.7M was sent to Shell on 9/19/2002, which encompassed the tasks described above. The cost can be reduced to approximately $1.5M by cutting the 10 weeks testing time by 25%. Results of the tests will include: documentation of salt hydration/ dehydration processes, salt heater performance, heat transfer results for 700' of insulated pipe, and well-head test results relating to differential thermal expansion of the insulated pipe.

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